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The Scientific Enterprise in India

Past Achievements, Present Trends, and Future Challenges

Editors

V.M. Tiwari
A.K. Singhvi

Commemorating
Nine Decades of
Service to
Science and Humanity

Indian National Science Academy

"If we desire to fight successfully the scourge of poverty and want from which 90 percent of our countrymen are suffering, if we wish to remodel our society and renew the spring of our civilization, and lay the foundation of a strong and progressive national life we must make the fullest use of the power which a knowldege of Nature has given us. We must rebuild our economic system by utilizing the resources of our land, harnessing the energy of our rivers, prospecting for the riches hidden under the bowels of the earth, reclaiming deserts and swamps, conquering the barriers of distance and above all, we must mould anew the nature of man in both individual and social aspects so that a richer, more harmonious and happier race may live in this great and ancient land of ours. Towards the realization of this ideal, we people must adopt ourselves to the new philosophy of life and train the coming generations for the services of the community in scientific studies and research".

– M.N. Saha

The Scientific Enterprise in India

Past Achievements, Current Trends, and Challenges in a Changing Socio-Techno-Economic Ecosystem

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Foreword

Science in India has always been more than a pursuit of knowledge; it has been a journey of nation-building, vision, and collective resilience. From the establishment of pioneering institutions to path-breaking discoveries, Indian science has consistently demonstrated its ability to adapt, evolve, and contribute to the global scientific discourse. Yet today, we stand at a defining moment. The scientific enterprise is navigating an era marked by rapid technological transformation, shifting societal expectations, ethical dilemmas, and an increasing demand for accountability and measurable outcomes.

This volume, *The Scientific Enterprise in India: Past Achievements, Current Trends, and Challenges in a Changing Socio Techno-Economic Ecosystem*, arrives at a timely juncture. It brings together the reflections of eminent scientists, former presidents of national academies, science leaders, and policymakers—individuals who have not only shaped the trajectory of Indian science but have also witnessed its evolution from close quarters. Through their insights, this book attempts to trace the legacy of scientific excellence in India, critically examine present-day challenges, and envision pathways for a more sustainable, ethical, and innovation-driven future.

What makes this work unique is its focus on the philosophy, principles, and governance of science rather than its outcomes alone. It raises essential questions: *How can we protect the core values of science when the world increasingly focuses on quick, practical outcomes?* What role should science academies play in upholding ethics, mentoring young researchers, and ensuring the dignity and safety of scientific practice? And how can India strike a balance between tradition and modernity in a rapidly changing socio-techno-economic landscape?

By revisiting milestone events, uncovering areas that needed improvement, and articulating opportunities for the future, this volume offers both introspection and inspiration. It encourages academia, policymakers, and the scientific community to rethink strategies, reaffirm core values, and collectively build an ecosystem where curiosity, responsibility, resilience, and societal relevance coexist.

I am confident that this book will serve not only as a chronicle of India's scientific legacy but also as a guiding compass for the generations to come. It is a tribute to the past, a mirror to the present, and a roadmap for the future of Indian science.

Ashutosh Sharma
President
Indian National Science Academy (INSA)

Preface

In the realm of sports, when a skilled athlete achieves a century or scores a decisive goal, there is often a moment of reflection where they assess their performance, contemplate missed opportunities, and adopt a renewed focus to continue with determination and energy. Similarly, organizations periodically engage in reflective practices to evaluate their performance, analyze their achievements, and refine their strategic plans. This process allows them to align their objectives with the changing socio-political, economic, and technological landscape, thereby reaffirming their commitment to a positive trajectory for the future. These occasions are a time to celebrate successes and a time for introspection and to establish the *raison d'être* for their very existence.

Over the past nine decades, the Indian National Science Academy (INSA) has played a pivotal role in advancing science in India—recognizing individual excellence, shaping advisories on science and society, and fostering global scientific connections. Today's world is transforming rapidly due to rapid technological advancements, shifting public perceptions, the invasion of social media and transactional and ethical attitudes globally. In India, the limitations of available resources occasionally present significant challenges to sustaining enthusiasm for scientific endeavors and their effective implementation among both practitioners and stakeholders. At the same time, society increasingly expects tangible and immediate returns from its investment in science. The securities and comforts provided by science have made societal expectations more transactional. It has moved away from valuing a *free play of free intellect* as an intellectual curiosity that at times leads to *seemingly useless science,* providing a *useful development tool for society,* to a more transactional approach to the extent of managing science and scientists for express returns.

We believe Science Academies and the academic community have a vital role in nurturing an informed, rational, and compassionate society strengthened by scientific advancement, available to all. This is a challenging mission: much of society contributes to science but doesn't directly benefit from it. Thus, academia and academies must take social responsibility in fostering accessible, innovative development for the greater good.

With this perspective, the idea of this book on The *Scientific Enterprise of India: Past Achievements, Current Trends and Future Challenges in a Changing, Socio-Techno-Economic Ecosystem* was conceived. We requested about 50 of the senior scientists of the county, who have substantially contributed to the development of the firmament of Indian Science. We sought their distilled vision with an explicit request to be both *preceptive* and *prescriptive* in their contributions. A clear mandate to them was to address the following statement, "*We often talk about what is not good in the Scientific and Education ecosystem, and this book will be the time ripe to record as to what could and should be done now, to secure the future that nurtures creativity, critical thinking and a merit-based, enabling system.*

The leitsatze for their contribution were:

a) Milestone events in Indian Science and key successes;

b) Areas where improvements could have been made;

c) The current state of Indian Science, including the author's specialty domains;

d) Future challenges and opportunities in a changing global ecosystem;

e) The guiding principle of academia in successful navigation in a changing world order and innovation of technologies that would impact societies of far future, comprising perfect strangers; and

f) The role of academies in future societal firmament in all its dimensions.

The response was enthusiastic, and we received 34 contributions, which are included as individual chapters in the book. These chapters cover a wide canvas of Indian science and are placed into three broad categories, viz.

a) Academies, Policies, Innovation and Entrepreneurship;

b) Education, Research and Ethics; and

c) Thematic thoughts.

It is expected that each of these articles would evoke deep thinking and generate intense discussion in the community, and would lead to some concrete actions. The chapters also include a narrative on various new initiatives at the governance and at the academy levels, provide a discussion on varied challenges in the future growth of science, raise concerns on ethical aspects and provide windows into development and anticipations from thematic issues. Though some chapters have seemingly

similar titles, each article provides a newer perspective, meriting serious attention.

It is encouraging to observe that various new initiatives are being developed at the governance level. However, one must await the implementation of these initiatives to determine whether they will be executed with the same enthusiasm and urgency with which they were conceived. The academies can play a pivotal role in preparing the nation for the forthcoming initiatives, including the fast implementation of the National Education Policy. They can facilitate the development of new mechanisms and synergies that enable India's scientific community to collaborate effectively, all with the unified objective of prioritizing national interests while contributing to global good.

The credibility of any scientific enterprise depends on its timely delivery of funding, procurement, results, their dissemination and their translation. Only then can we be future-ready and be at a competitive level in the comity of nations. Some common concerns that are already in the public domain and are being discussed at various levels have also been highlighted by many. These include the level of funding, the ease of doing science, the bureaucratic delays tempered with excessive regulation and a rapid erosion of ethics. Another concern has been the level of financial support, which in real terms is close to only a few per cent of many developing and developed nations. We also need to build a capacity that is an order of magnitude higher than at present. While there are concerns, there also appeared to be good hope that India's progressive policies and collective scientific understanding would carve a path toward meeting expectations. The chapters in this book discuss these issues and provide several possible solutions.

The academies have a role to play in providing new ideas and possibilities to the Governance systems. It is, therefore, heartening to note that several initiatives of the academies have now resulted in affirmative action by the governance firmament. Thus, the joint suggestion of academies for one nation one subscription, on ethics in science, on ethics, on animal trials, and on the improvement of institutional ranking system are being addressed to. The academies will need to do more of such efforts proactively, in providing guidelines and frameworks. We all have a role to play to help the nation build its scientific firmament for societal delivery. Establishment of the policy cell at INSA is a welcome step, and we hope it becomes a meaningful mechanism to interface science with Governance and Society.

We do not wish to preempt the chapters by discussing them here and will leave the readers to explore each one of them. All we can ensure is that each one of them is a rare nugget of wisdom. A conscious omission

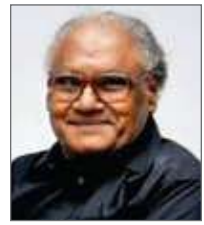
was the contribution by the younger scientific community, due largely to time and other constraints, and we do hope a successor compendium will complement this book. Their views, as the future deliverers, would matter equally.

Reading and editing the chapters were personally enriching, and we would like to express our gratitude to all the esteemed authors for their sage contributions, as well as for their patience with our edits and suggestions. We thank the President, INSA, the Vice Presidents and the Council for approving our suggestion for such a book commemorating 90 years of INSA. We thank the INSA staff for their help and M/s Angkor Publishers Pvt Ltd., for their willing diligence in expeditiously converting individual articles into an elegant compendium, in a short time.

We would like to end by remembering two quotes. The first from Dr. Vikram Sarabhai, *that to be respected, one should assume responsibility*. The second are the famous words of the first Prime Minister of Independent India, who on August 15, 1947, said, *….long time ago we made a tryst with destiny, and now the time comes when we shall redeem our pledge, not wholly or in full measure, but very substantially*. This is a critical moment for academies and academia to embrace their responsibilities, earn society's respect, and help deliver a scientific, capable, and inclusive India—where dignity, purpose, hope, and creativity thrive.

V.M. Tiwari
Jorhat

A.K. Singhvi
Shantou / Ahmedabad



Message

As INSA completes 90 years of its scientific journey, it stands at a pivotal moment rooted in a rich tradition of discovery while actively shaping the frontiers of modern science.

My years at INSA were amongst the most glorious and fulfilling of my career — at times marked by intellectual camaraderie, national service and the joy of being part of a great scientific tradition.

Science in India has made remarkable strides, with growing global visibility, a strong institutional framework, and impactful contributions across space, health, agriculture, and digital technologies. While challenges like low R&D investment and talent retention persist, there is renewed momentum through national missions, innovation-driven policies, and a focus on societal relevance.

As INSA marks 90 years, it continues to play a vital role in shaping Indian science and inspiring future generations and played a central role in guiding and nurturing this progress, championing scientific excellence, policy dialogue and the promotion of scientific temper. As India enters a new era, the foundation laid by INSA over nine decades continues to inspire the future generation of scientists to serve society through knowledge and innovation.

C.N.R. RAO

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C.N.R. RAO is a renowned Indian chemist widely regarded as a metaphor for Indian science, is bestowed with the highest civilian honour of India, "Bharat Ratna". A world's leading figure in solid-state and materials chemistry, through his more than 1,700 research publications and 50 books, is often described as a scientist who has won all possible awards in his research field except the Nobel Prize. He obtained an MSc degree from Banaras Hindu University and earned a PhD from Purdue University at the age of twenty-four. He has been a faculty member at IISc, Bangalore and IIT Kanpur and was the Director of the IISc from 1984 to 1994. As the founder of the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in Bangalore (1989), he serves as its Honorary President and Linus Pauling Research Professor. He also founded and directs the International Centre for Materials Science (ICMS), established in 2008. From 1985 to 1989 and again from 2005 to 2014, he held the position of Chair of the Scientific Advisory Council to the Prime Minister of India. He served as President of the Indian National Science Academy during 1985-1986.

Academies: Policy, Innovation and Entrepreneurship

Evolving Role of the Indian National Science Academy: Towards Democratizing Science, Nurturing Leadership, and Shaping India's Scientific Future

Ashutosh Sharma

Scope

India stands today at a defining inflection point in its scientific evolution. Fuelled by expanding technological ambitions, a burgeoning research workforce, and rising global expectations, the national landscape of science, technology, and innovation is transforming at a velocity unseen in previous decades. While the nation has secured commanding heights in domains such as space exploration, digital public infrastructure, biotechnology, and clean energy, the broader scientific ecosystem continues to grapple with persistent structural dichotomies. We face a landscape marked by excellence in islands of strategic research, yet contrasted by fragmented capacity in the university sector, uneven resource distribution, and distinct barriers to the "ease of doing science". These wider national realities, of a dual economy of knowledge, form the complex backdrop against which the role of a national academy must be re-imagined.

In this contemporary milieu, modern academies can no longer remain *ivory towers* limited to the passive recognition of established excellence. Their mandate must expand to encompass the active stewardship of scientific culture. The responsibility of an Academy today extends to strengthening the scientific temper, promoting ethical transparency, broadening participation across demographics, and building

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robust bridges between science, society, and the state. By identifying systemic gaps and enabling collective action, national academies must serve not merely as honorific bodies, but as vital conduits between scientific knowledge and national development.

It is within this broader context that the Indian National Science Academy (INSA), as it approaches its 91st anniversary in 2025, finds itself in a period of deep institutional reflection and renewal. Since its founding in 1935 [1], INSA has been the custodian of scientific excellence in India, mirroring the nation's own journey from colonial constraints to post-independence self-reliance. However, the demands of the 21st century are vastly different. Today, public trust must be earned, ethics must be codified, and scientific advice must be integrated meaningfully into the policy matrix. Science is no longer confined to the laboratory or the peer-reviewed journal; it is deeply entangled with community aspirations, industrial growth, and global sustainability challenges.

To address these systemic shifts, the Academy has initiated a structural transformation rooted in the principles of democratization and relevance. Recognizing that the future of science depends on the diversity of its practitioners, INSA has moved to widen the scientific community it represents. This is evident in the inclusion of Young Associates and Associate Fellows; measures designed to bridge the intergenerational gap and bring youthful energy into the Academy's fold. Concurrently, the establishment of the INSA Women's Association acknowledges the imperative of gender equity, ensuring that the voices guiding the national agenda reflect the true diversity of Indian intellect.

Furthermore, the Academy is redefining what constitutes scientific contribution. By creating new fellowship categories such as *Science in Translation* and *Science for Society*, INSA is signalling that the translation of knowledge into societal benefit is as valuable as fundamental discovery. To institutionalize the critical link between evidence and governance, the Academy has formed the Centre for Science, Technology and Innovation Policy (CSTIP) [2], positioning itself as a reservoir of data-driven policy advice. These structural reforms are underpinned by robust capacity-building initiatives, such as the LEADS Programme (Leadership Development in Science) and the 'Navigating PhD and Beyond' workshops, which are designed to equip the next generation of researchers with the soft skills and strategic vision necessary to navigate a complex global landscape.

Through these collective efforts, INSA is transitioning from a traditional academy of distinguished scholars into an institution that is inclusive, transparent, collaborative, and deeply connected to national priorities. Its renewed vision aligns scientific merit with societal utility,

reinforcing the integration of science and policy, and positioning the Academy as an essential, proactive architect of India's scientific future.

India's S&T landscape: The paradox of scale

Over the past two decades, the nation has made remarkable strides in frontier fields, expanded its research output to become the world's third-largest producer of scientific publications, and cultivated a vibrant innovation ecosystem. Yet, the landscape is more complex, demanding, and interconnected than ever before. To understand the mandate of a modern academy, one must first confront the *Paradox of Scale* that defines Indian science today: we are witnessing high-velocity growth alongside persistent structural inertia.

On the surface, the metrics of progress are undeniable. As the 2025 NITI Aayog report [3] elucidates, India's Gross Expenditure on Research & Development (GERD) has nearly doubled over the past decade, rising from ₹ 60,196 crore in 2010–11 to ₹ 127,380 crore in 2020–21. This financial expansion reflects a resolute national commitment to strategic sovereignty in sectors such as Artificial Intelligence, quantum technologies, space science, and digital public infrastructure.

However, a deeper interrogation of this data reveals a structural vulnerability. The architecture of Indian R&D investment is heavily skewed. Nearly half of the national R&D expenditure (43.7%) flows from the central government, while state governments, the primary custodians of local education and development, contribute a meagre 6.7%. Furthermore, the contribution from higher education institutions stands at just 8.8%. This profound imbalance creates a centripetal scientific ecosystem where resources, talent, and capabilities are disproportionately concentrated in a handful of elite national institutions. Meanwhile, the vast network of state universities, which educates the majority of India's youth, remains on the periphery of the innovation economy. This centralization poses a severe risk: while India creates islands of global excellence, the mainland often struggles with outdated infrastructure and limited capacity. For India to transition from a *knowledge consumer* to a *knowledge creator*, investment must not only be increased but democratized.

Financial resources, nonetheless, are not the exclusive factor influencing scientific achievement. The ecosystem is currently hindered by persistent systemic gaps, frictions that slow the velocity of innovation. First, there is the challenge of fragmentation. The interfaces between academia, industry, and the state remain underdeveloped. In mature scientific economies, these sectors operate as a triple helix, constantly exchanging personnel and ideas. In India, they often function as silos. The ease of doing research varies wildly across institutions, frequently

hampered by bureaucratic bottlenecks in procurement and lifecycle management, issues explicitly targeted by recent policy interventions like SRIMAN [4], but which require deeper cultural implementation.

Second, we face a crisis of inclusivity and culture. The Indian knowledge pool, though vast, is restricted by historical exclusions. Gender imbalances persist, particularly in leadership roles; young scientists are often marginalized in decision-making processes; and researchers from emerging institutions outside the metropolitan hubs struggle for visibility. A transformative scientific vision requires a behavioural shift: moving from a hierarchical, seniority-based culture to one of collaborative leadership and open inquiry.

Third, there is the critical bottleneck of state-level capacity. As noted by NITI Aayog, State S&T Councils often suffer from fragmented mandates and low institutional capacity. This is a critical fracture point because many of India's most pressing challenges, water resource management, climate resilience, agriculture, and public health, are fundamentally local issues that require state-driven scientific solutions. Without robust local ecosystems, national solutions often fail to find purchase on the ground.

Finally, there is the emerging imperative of governance and ethics. As India takes a lead in dual-use technologies like genomics and AI, the moral responsibility of the scientific community increases. The integration of high-quality, independent scientific advice into policymaking remains uneven. We face a future where complex challenges, from climate unpredictability to algorithmic bias, require solutions that are not just technically sound, but ethically robust and socially responsive.

In this volatile landscape, the role of a National Academy becomes not just relevant, but existential. What, fundamentally, is an academy for in the 21st century? Globally, the purpose of a scientific academy is dual-fold: to act as the custodian of scientific integrity and as a catalyst for knowledge-driven development. Academies are the foundational intellectual anchors in a rapidly changing world to provide the long and sustained view for stewarding the nation's scientific aspirations over decades. They serve as credible, independent platforms for evidence-based policy advice, shielding scientific truth from the noise of misinformation, a critical function in our current "post-truth" era. Crucially, they act as the connective tissue of the ecosystem, forming knowledge networks that link the disparate worlds of universities, national labs, industry, and the global diaspora. By upholding the gold standards of peer review and ethics, and by actively mentoring the next generation of leadership, the Academy ensures that science serves the public good, rather than private interest alone.

INSA at 90: A legacy of Nation-Building

As INSA approaches its 91st year in 2025, it stands at a juncture defined by its storied past and its evolving future. To map the trajectory forward, we must appreciate the vision that birthed it. INSA was not founded merely as a learned society; it was conceived as an act of intellectual sovereignty. Established as the National Institute of Sciences of India (NISI) on January 7, 1935, in Calcutta, the Academy emerged from the nationalist ferment of the independence movement. Visionaries like Meghnad Saha, J.H. Hutton, and L.L. Fermor, alongside leaders of the Indian Science Congress Association, recognized that a colonial dependency could not foster indigenous scientific self-reliance. They saw the urgent need for a unified voice for the Indian scientific community, one that could represent the nation on the global stage with dignity and authority.

The evolution of the Academy mirrors the evolution of the modern Indian state. In October 1945, the Government of India formally recognized NISI as the premier scientific society of the country. This was a pivotal moment, transitioning the body from a private association to a national institution. The physical shift of its headquarters from Calcutta to Delhi in May 1946, and later to its permanent campus in 1951, with the foundation stone laid by the then Prime Minister Jawaharlal Nehru, symbolized the integration of science into the heart of the new republic's governance.

By 1968, the Academy was formally mandated to represent India at the International Council for Science (ICSU), and in 1970, it adopted its present name, the Indian National Science Academy (INSA). Throughout these decades, INSA did not sit on the sidelines. Its Fellows were instrumental in drafting the historic **S**cientific Policy Resolution of 1958, which for the first time declared that the key to national prosperity lay in the effective combination of technology, raw materials, and

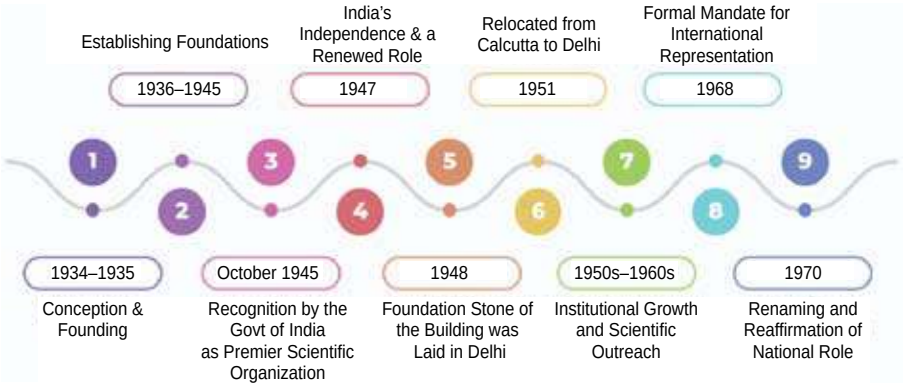

Figure 1: Founding vision of Early years

capital. Thus, the Academy has always been more than a witness to history; it has been an active participant in the architecture of modern India.

The changing contract: Why academies must evolve

The landscape of science in the twenty-first century is undergoing a transformation that is not merely structural, but ontological. For the better part of the last century, scientific academies were designed with a relatively static mandate: to recognize individual merit, to promote scholarly exchange within disciplinary silos, and to serve as the guardians of historical prestige. However, the world in which these institutions now operate has shifted on its axis. Science is no longer a solitary pursuit conducted behind the closed doors of a laboratory; it is an endeavour that is expected to be deeply interdisciplinary, rigorously ethical, socially embedded, and intimately responsive to the chaotic pulse of real-world challenges. These expanding expectations have rewritten the "social contract" between the scientist and the state, creating new responsibilities for academies like INSA. The demand is clear: we must pivot from traditional, honorific functions towards a role that is active, integrative, and aggressively future-oriented.

The most immediate driver of this evolution is the changing nature of the problems we face. The challenges confronting India today, ranging from climate resilience and public health crises to energy transitions, AI governance, food security, and sustainable urbanization—possess a complexity that defies the boundaries of any single discipline. A physicist alone cannot solve the energy crisis; it requires materials scientists, economists, and sociologists working in concert.

Consequently, the global research paradigm is shifting from individual scholarship to team science and mission-driven national programs. We see this in global initiatives such as Mission Innovation and Future Earth, which organize science around shared grand challenges rather than narrow academic fields. India's own recent triumphs offer a testament to this integrated approach. The success of Chandrayaan-3, the rapid mobilization for the COVID-19 response, and the rollout of our Digital Public Infrastructure were not victories of isolated genius, but of ecosystem-level coordination. They demonstrated the immense power of cross-pollination between disciplines, institutions, and sectors. In this context, a modern academy cannot function merely as a roster of distinguished individuals. It must act as a National Integrator, a convening power capable of bringing diverse expertise together to address national priorities that sit in the white spaces between established departments.

Parallel to the shift in *how* science is done is the urgent necessity to rethink *who* is doing it. Science today must reflect the diversity of the society it serves, yet we face persistent structural gaps. Women remain critically underrepresented in higher scientific leadership; young researchers often find their voices marginalized in decision-making; and "excellence clusters" remain disproportionately concentrated in a few metropolitan hubs, leaving the vast talent pool of state universities and rural India untapped.

This is not merely an issue of social equity; it is an issue of national economic strategy. As India marches towards the ambitious target of a $5 trillion economy by 2027 [5], relying on a narrow demographic base for innovation is a strategic error. A knowledge-powered growth model requires the full utilization of the nation's intellectual capital – across all genders, regions, and social strata. The Academy must, therefore, widen its intellectual ecosystem. We must actively create pathways for first-generation learners, tribal communities, and researchers from emerging institutions, ensuring that the scientific leadership of tomorrow is not a mirror of the past.

As the footprint of science expands into every facet of human life, the moral responsibility of the scientific community grows in proportion. The emergence of powerful technologies, from Generative AI to gene editing, brings with it profound concerns regarding safety, data governance, and biosecurity. As emphasized by OECD [6] guidelines, responsible research is now central to global science governance.

In this volatile environment, the Academy must serve as the custodian of the scientific conscience. It is our duty to champion rigorous ethical standards, enforce conflict-of-interest norms, and ensure absolute integrity in peer review and fellow elections. This ethical stewardship is the bedrock of public trust, which is currently under siege. The digital revolution, while democratizing access to information, has also accelerated the spread of misinformation, particularly in critical areas like health and agriculture. Research indicates that false news spreads six times faster than verified scientific content. In this atmosphere, the Academy's role in strengthening the "scientific temper" is existential. We must engage proactively with media, policymakers, and educators to communicate science clearly and credibly, acting as a lighthouse of evidence in a sea of noise.

The evolution of the Academy is driven by the need for evidence-informed governance. Modern statecraft requires policymaking that is grounded in data, not anecdote. Globally, scientific institutions are moving from the role of passive observers to active contributors in the policy process, producing consensus reports, guiding long-term

planning, and responding to national emergencies. Documents such as the draft STIP-2020 [7] and the NITI Aayog Roadmap underscore this shift, positioning scientific institutions as essential partners in national development. For India to harness its demographic dividend and compete globally, science must sit closer to the seat of governance. Academies are the natural bridges between these two worlds.

Collectively, these shifts, methodological, demographic, ethical, and political, redefine the purpose of the Indian National Science Academy. We are called to transition from an inward-looking scholarly body to an outward-facing, ecosystem-shaping institution. Our new mandate is to convene, to empower, to protect, and to guide. By strengthening institutions and linking science inextricably with society, we ensure that the Academy remains not just a monument to past achievements, but the architect of India's scientific future.

The reform agenda (2023–2025): A vision-led transformation

To address the systemic gaps in Indian science and respond to the changing demands of the twenty-first century, INSA undertook a series of transformative initiatives between 2023 to 2025. This period marks one of the most significant phases of institutional renewal in the Academy's recent history. This transformation was not merely administrative; it was conceptual, rooted in a deliberate effort to realign the Academy with the

Figure 2: New initiatives (2023–2025)

evolving expectations of science, society, and national priorities. The Academy restructured its processes, culture, and modes of engagement to become more inclusive, transparent, participatory, and future-ready. These reforms were guided by a broader vision of what a modern academy must represent: an institution that builds ecosystems rather than just celebrating excellence; that nurtures leadership rather than merely rewarding seniority; and that connects science to society, not only to itself.

Redefining membership: Building the academy family

For much of its history, scientific academies in India were perceived as exclusive spaces reserved largely for established senior scientists. While this ensured a standard of academic excellence, it unintentionally created a chasm between the Academy and the vital demography of young scientists, women researchers, and innovators. In recent years, INSA has consciously moved to bridge this gap by expanding the concept of the Academy Family.

A primary focus has been the injection of youth into the Academy's bloodstream. Instead of limiting recognition to late-career elections, INSA introduced categories such as Associate Fellows (for those under 50) and Young Associates (for those under 40). This tiered structure allows emerging scientists to receive early recognition and contribute their energy and technological competence to national scientific discussions. This commitment to the next generation is further reinforced by the Indian National Young Academy of Sciences (INYAS). Established by the INSA Council, INYAS has grown into a vibrant body of 119 members who drive science outreach, career workshops, and technical symposiums across the country, ensuring that the voice of the young researcher is heard by policymakers.

Simultaneously, the Academy has taken historic steps to address gender disparity. In 2025, INSA launched the INSA Women's Association (IWA), inducting a foundational cohort of 70 women leaders from academia & R&D labs, government, startup and NGO/society, industry. The Council has approved induction of 70 Women Associates annually until the strength of IWA reaches 350 in the next five years thus integrating a wide spectrum of women leadership in the INSA family to drive new initiatives. By engaging these leaders for a five-year term, the Academy is not only recognizing their contributions but actively integrating them into committees and decision-making platforms, thereby correcting historical imbalances in scientific leadership.

Democratizing science: Expanding stakeholders and recognition

Traditionally, the stakeholders of a science academy were viewed narrowly as the creators of knowledge-university professors and laboratory researchers. However, the contemporary landscape of science encompasses those who translate, govern, and apply that knowledge. Recognizing this shift, INSA has broadened its stakeholder base and introduced new mechanisms to honour diverse contributions.

This is most visible in the introduction of two pioneering fellowship categories [8]. The *Science in Translation* fellowship acknowledges leadership beyond traditional academia, specifically targeting innovators in industrial R&D and managers of critical technology missions. Concurrently, the *Science for Society* [6] fellowship celebrates individuals who apply scientific knowledge to solve developmental challenges at scale-in health, water, agriculture, and climate, as well as those who have popularized science among the masses.

This spirit of democratization has also transformed the Academy's public interface. The Anniversary General Meeting (AGM), once a closed procedural event, has been reimagined. The 2024 AGM engaged over 5,000 participants, and the 2025 AGM is set to be celebrated as a full-scale Science Week across Delhi-NCR institutions. By involving universities and students directly, the Academy is signalling that science is a public trust, not a private enterprise.

Institutionalizing governance: Policy, ethics, and agility

As the scientific enterprise grows in complexity, the Academy's internal machinery has been upgraded to ensure accountability, transparency, and relevance. A critical structural reform was the introduction of a Vice-President for Policy, a new portfolio designed to align INSA with global academies that serve as principal advisors to their governments. This strategic pivot was institutionalized through the establishment of the Centre for Science, Technology and Innovation Policy (CSTIP) in October 2024 supported by funding from DST. Guided by an expert advisory board, CSTIP has already begun generating evidence-based policy inputs, including the proposal for a national document on the *Top 100 S&T Challenges for India*.

To ensure the Academy remains responsive to emerging frontiers, the Sectional Committees were restructured. A new committee for "Interdisciplinary Science and Engineering: Deep Tech and Critical Technologies" was introduced, creating a dedicated space for experts in AI, quantum technologies, and 6G. Furthermore, to prevent stagnation,

a staggered tenure system was introduced for committee members, ensuring a balance of continuity and fresh perspectives.

These structural changes were underpinned by rigorous ethical reforms. To maintain the credibility of the Fellow election process, INSA introduced mandatory Conflict-of-Interest Declaration forms and deployed independent observers in Sectional Committee meetings. The evaluation criteria were refined to emphasize qualitative impact over mere publication numbers, ensuring that the selection process remains rigorous, fair, and transparent.

Capacity building, global engagement, and infrastructure

Beyond governance, the Academy has significantly expanded its role in capacity building and international diplomacy. The flagship LEADS Programme (Leadership Development in Science & Technology), conducted in collaboration with the National Centre for Good Governance, addresses the critical need for administrative and leadership skills among mid-career scientists. Notably, this program includes specific financial support for women scientists through a partnership with the American Chemical Society (ACS). Additionally, the new ESG Training Programme with IIT Roorkee prepares researchers to integrate sustainability and social responsibility into their work.

On the global stage, INSA has asserted India's scientific leadership. As the knowledge partner for the Science20 (S20) engagement group during India's G20 Presidency in 2023, INSA led global deliberations across various aspects of transformative technologies led development. Bilateral ties have also been strengthened, notably through the INSA-Royal Society Policy Dialogues, which have created an institutionalized mechanism for high-level exchange between India and the UK.

Domestically, the Academy has also revitalized its publishing and physical infrastructure. The editorial board of the *Proceedings of the Indian National Science Academy (PINSA)* was reconstituted, helping the journal achieve an impact factor of approximately 2.1–a twenty-year high. Simultaneously, the physical campus and guest house are undergoing comprehensive modernization to better serve the scientific community.

A future vision: India's scientific pathway to Viksit Bharat@ 2047

As India enters a decisive phase in its development, looking towards the centenary of its independence in 2047, the role of the national academy must evolve to meet the aspirations of a rising knowledge power. The

future vision for INSA is grounded in a profound principle: a modern academy must not only reflect the state of science but actively shape its future.

This vision is anchored in ethics, transparency, and inclusion. In an era of rising misinformation and complex societal challenges, ethical leadership is as vital as scientific brilliance. INSA must act as the guardian of scientific values, ensuring that research is conducted responsibly and communicated truthfully.

For India to become a global S&T leader by 2047, the Academy advocates for five strategic shifts:

Decentralization of Growth: India must move beyond a centralized model. We must increase R&D investment while aggressively strengthening State S&T Councils and regional universities. The vibrancy of the national system depends on the connectivity of the entire ecosystem, not just a few elite islands.

World-Class Research Universities: The *Ease of Doing Research* must become a priority. This entails reducing administrative burdens, streamlining funding approvals, and supporting long-term, curiosity-driven research alongside mission-oriented programs.

Responsible and Open Science: India must establish robust national frameworks for research integrity, data governance, AI safety, and open-access publishing to align with global standards.

The Industry-Academia Bridge: We must accelerate the translation of knowledge into innovation. Academies must play a catalytic role in convening researchers, entrepreneurs, and policymakers to co-create solutions in sectors like space, pharma, and digital public goods.

Frontier Missions: India must launch long-term, interdisciplinary missions in areas such as quantum technologies, advanced materials, and climate resilience.

In the spirit of *Amrit Kaal*, this vision places a renewed emphasis on youth. With a demographic advantage anchored in a vibrant community of young researchers, the nation's scientific future depends on how effectively we empower them. By strengthening fellowships, expanding leadership programs, and ensuring meaningful representation, INSA aims to be the lighthouse that guides India's journey towards a sustainable, inclusive, and knowledge-powered future.

Conclusion: From reflection to responsibility

As the Indian National Science Academy approaches its 91st anniversary, it finds itself at a pivotal moment, one defined by both its

esteemed legacy and its renewed dedication to the future of the nation. The structural transformations undertaken between 2023 to 2025 represent far more than administrative recalibration; they signify a fundamental reimagining of the Academy's purpose in a rapidly evolving scientific landscape. We have decisively pivoted from being a static institution primarily driven by recognition to a dynamic, forward-looking engine focused on ecosystem building, leadership curation, and the strengthening of the vital interface between science and society.

The specific reforms of the past few years opening the Anniversary General Meeting to the wider community, institutionalizing the voice of young and women scientists, reforming the metrics of election, and decentralizing outreach to state and private universities — are distinct components of a singular vision. They reflect a growing realization that true scientific excellence cannot exist in a vacuum; it must be grounded in inclusion, transparency, and ethical conduct. These changes demonstrate that a national academy in the twenty-first century must evolve from a ceremonial "high table" into an active contributor to national capability-building.

This evolution is necessitated by the changing social contract of science. Today, the boundaries between the laboratory and the public square have dissolved. The responsibilities of the scientist now extend beyond the generation of data to the stewardship of public trust, the communication of complex realities, and the engagement with policy on existential challenges such as climate change, sustainability, and equity. INSA's strategic initiatives, from the leadership training of the LEADS programme to the expanding portfolio of thematic workshops, are designed to equip India's scientific community with the multidimensional skills required to navigate this complexity.

As India accelerates towards its centenary in 2047, the aspiration to emerge as a global knowledge power demands an Academy that is agile, ethical, and future-ready. INSA's long-term vision is intimately aligned with national priorities: strengthening state-level research ecosystems, revitalizing the university sector, investing in the demographic dividend of young researchers, and fostering deep, distinct collaborations between industry and academia. Furthermore, the establishment of the Centre for Science, Technology and Innovation Policy (CSTIP) marks a critical maturation of the Academy, institutionalizing the flow of evidence-based advice to the state and elevating the scientific voice in the corridors of governance.

Looking ahead, the core mandate of the Academy remains immutable, yet its expression must be contemporary. We remain the custodians of scientific excellence and the champions of integrity. However, we

must also serve as the bridge that connects the disparate islands of the ecosystem. The Academy must provide leadership that is grounded not only in intellect but in values, ensuring that Indian science remains globally competitive, nationally relevant, and socially responsive.

INSA at 90 is not merely a moment of celebration; it is a moment of profound responsibility. We are charged with carrying forward the momentum of these reforms to shape a scientific culture that is collaborative rather than hierarchical, and future-oriented rather than nostalgic. With its renewed vision, strengthened governance structures, and expanded engagement, the Indian National Science Academy is well-positioned to serve as the moral and intellectual compass for India's scientific journey in the decades to come.

Acknowledgement

The only constant in the life of an organization is change! Both INSA and I are grateful to the collective resolve and forward-looking stance of the Vice Presidents, Council and indeed its entire fellowship that steered and strongly supported the new directions and seeding and growth of substantial activities in 2023-25. I am also deeply indebted to Famida Khan & Pranav Sharma of the INSA–Centre for Science, Technology & Innovation Policy for their ability to research and shape this chapter.

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ASHUTOSH SHARMA currently serves as the President of the Indian National Science Academy for the term 2023-2025. He previously held the position of Secretary to the Government of India in the Department of Science & Technology. Prof. Sharma is the Institute Chair Professor and the founding Coordinator of the Nanosciences Center and the Advanced Imaging Center at the Indian Institute of Technology in Kanpur. He earned his PhD from the State University of New York and has occupied various academic roles, including research faculty at SUNY Buffalo, as well as visiting positions at several prominent international universities. His interdisciplinary research encompasses fields such as nanotechnology, thin polymer films, and nanocomposites, among others. Ashutosh Sharma has authored over 400 peer-reviewed publications and holds more than 15 patents. He has received numerous accolades, including the Infosys Prize, TWAS Science Prize, Bessel Research Award, J.C. Bose Fellowship, S.S. Bhatnagar Prize, UNESCO Medal, H.K. Firodia Award, and the Padma Shri. Additionally, he has been conferred with nine honorary Doctor of Science degrees from universities in the United States and India. Ashutosh Sharma is also an elected Fellow of several prestigious organizations, including the Indian National Science Academy, the Indian Academy of Sciences, the National Academy of Sciences, India, the Indian National Academy of Engineering, The World Academy of Sciences (TWAS), and the Asia-Pacific Academy of Materials. Furthermore, he has served as an editor for various scientific journals. His interests also extend to ancient history, philosophy, poetry, and the arts.

2

Strengthening Science-Policy Interface: Charting India's S&T-led Transformation

A.K. Sood*, D. Lingayat, B. Chagun Basha and P. Maini

Scope

As the global economy shifts decisively towards knowledge-driven models, science and technology (S&T) have become indispensable engines of transformation. Beyond their traditional roles in innovation and advancement, in the present times, S&T form the backbone of policymaking for effective governance and national development. In this shifting landscape, science is more than a driver of sectoral progress; it has to stand as a cornerstone of governance that is resilient, responsive, and equipped for the future.

India's development journey reflects this paradigm shift. The integration of science-informed policy and advisory mechanisms has catalysed progress across multiple sectors and is poised to play an even more strategic role in steering the nation's future. Science advice is now central to designing agile policies, ensuring effective implementation, and enhancing institutional resilience.

This contribution examines the catalytic role of science advisory systems in shaping India's scientific and technological trajectory. It explains the manner in which institutions such as the Office of the Principal Scientific Adviser to the Government of India (OPSA) are facilitating this transformation by developing and guiding S&T missions for the nation's well-being by, fostering collaborations with and between stakeholders, strengthening scientific infrastructure and ensuring their access on an equal opportunity basis, and increasing India's engagement in global policy platforms.

Looking ahead, the article discusses the manner in which data-driven foresight, systems thinking, and anticipatory governance can equip India to navigate through technological disruptions and societal

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complexities. As the pace of change accelerates, strengthening the science-policy interface will be the key, not only in sustaining national progress but also in ensuring India's effective presence in the global discourse on science, technology, and innovation.

Introduction: Science advisory at the heart of public policy and governance

The evolution of India's science-policy interface, or the science advice mechanism, is a result of 78 years of scientific vision, institution-building, and the integration of science with society, economy, and polity. Today, India is among a handful of countries with a well-established science advice mechanism that blends scientific knowledge with decision-making, public engagement, and institutional transformation. Evidence-driven, public-facing, and outcome-oriented science advice is critical now more than ever due to the growing complexity of the technoscientific evolutions and their socio-economic repercussions [1]. To understand how a strong and future-facing science-policy interface can be built, we enumerate some of the key milestones in India's path to a societally meaningful scientific enterprise, assess contemporary needs and anticipate the future trends.

The adventurous yet critical need for a scientific temper was made fundamental to the country's ethos as we earned our independence and became a republic. This era (1947-1967) was a period of institution building, where the Council of Scientific and Industrial Research (CSIR) saw its expansion, the first set of Indian Institutes of Technology was established, and the Departments of Scientific Research, Space and Atomic Energy were established. The Science Policy Resolution of 1958 [2] laid the foundation of India's scientific enterprise, which was built on the tenets of scientific temper and which saw science and technology as a tool for socio-economic transformation [3]. Dr Shanti Swarup Bhatnagar, Dr Homi Bhabha, Dr Vikram Sarabhai, and Dr C.V. Raman were among the architects of this transformation [4]. Following the SPR 1958, the investment in the scientific enterprise grew manyfold, and numerous scientific organisations and laboratories were established. The Technology Policy Statement (TPS) 1983 [5] used this foundation and focused on two key elements of technological self-reliance and indigenous technology development. Science and Technology Policy (STP) 2003 [6] and Science, Technology and Innovation Policy (STIP) 2013 [7] aimed to integrate science with technology and later with innovation to enable the nation to be globally competitive.

The evolution of science advisory in India

The trajectories of India's scientific enterprise and the science advice mechanism have been intricately interwoven. The constitution of the Advisory Committee for Coordinating Scientific Research (ACCSR) was the very first post-independence step that recognised the need for science advice. Thereafter, the Scientific Advisory Committee to the Cabinet (SACC) was constituted in 1956 to provide scientific advice for decision-making to the government. SACC was followed by Committee on Science and Technology (CoST, 1968-1970), National Committee on Science and Technology (NCST, 1971-80), Scientific Advisory Committee to the Cabinet (SACC, 1981-1985), and Science Advisory Council to the Prime Minister (SAC-PM, 1986-1990). These variously helped the country to strengthen its science advice mechanisms.

The Office of the Principal Scientific Adviser (OPSA)[1] was established in 1999 with Dr A.P.J. Abdul Kalam as the first Principal Scientific Adviser. OPSA works on a larger canvas of the Indian Science firmament, creating synergies between departments and establishments to provide a seamless mechanism for science advice. OPSA has a singular mandate of providing evidence-based and policy-focused science advice to the Prime Minister and the Cabinet on all matters related to Science, Technology, and Innovation (STI). Further, in 2018, the Prime Minister's Science, Technology and Innovation Advisory Council (PM-STIAC) was established to streamline the efforts under SACC and SAC-PM, to inform national policies and initiatives.

Since its inception in 1999, the mandates and functions of the OPSA have increasingly expanded. It now advises on critical and emerging technologies, actively participates in international fora, and engages with the public to instil trust in scientific enterprise. This trajectory has been captured in the June 2025 edition of OPSA's Vigyan Dhara Magazine, which also marks 25 years of the OPSA [8].

OPSA has been emphasising the infusion of rigorous scientific evidence into policymaking. Through this, it has developed numerous national initiatives such as the National One Health Mission, One Nation-One Subscription Initiative, National Quantum Mission, Artificial Intelligence Mission and several others.

A milestone institution for India's research governance, Anusandhan National Research Foundation (ANRF), was conceptualised by the PM-STIAC. The sector-agnostic nature of science advice and its mandate to synergise diverse stakeholders were leveraged through each one of these initiatives. Through such initiatives, OPSA informs decisions and lends

1 Office of the Principal Scientific Adviser to the Government of India. https://www.psa.gov.in/

credibility, transparency and scientific reason for specific public policy choices. OPSA safeguards that the advisory process is inclusive and public-facing and ensures this through open dialogues, community-wide consultations and effective outreach. India's science academies have served as guardians of scientific temper and public trust. By proactively shaping the narratives and communicating consensus scientific knowledge, OPSA and the academies have synergistically fostered an environment where science is seen as a credible, inclusive, socially conscious enterprise that merits the confidence and trust of society.

In the following specific examples of instruments of science advice that translate this vision into action are discussed.

Instruments of science advice

Within India's governance framework, OPSA translates scientific knowledge into science advice to navigate the ecosystem and public policy. The office serves as a synergising platform where diverse expertise converges to inform decisions. Through carefully constructed partnerships with stakeholders spanning central and state governments, research institutions, and the industry, OPSA ensures that policy choices are evidence-based and takes cognisance of the depth, nuance and confidence levels of varied scientific inputs.

The office's mandate encompasses both advisory needs in real time and for longer-term strategic concerns, India's interests to determine its trajectory in the STI space. OPSA recognises that effective science advice requires understanding not only of what the research reveals, but also how those insights can be meaningfully utilised within existing institutional frameworks and resource constraints. This perspective shapes the office's approach to continually develop novel innovation ecosystems and maintain a vigil on emerging technological domains that may require policy interventions in the near future.

Central to OPSA's activities is the recognition that contemporary challenges cannot be adequately addressed by inputs from traditional disciplinary boundaries. Thus, for example, Climate change intersects with agriculture, energy, urban planning besides human migration and attendant sociological ramifications, accentuated ecological and geological hazards. Similarly, the emerging digital technologies are reshaping education, healthcare, the future of jobs and governance itself and how the nation can be equipped to meet associated challenges in a well-orchestrated manner. The OPSA, therefore, emphasises a systems thinking, identifying connections and opportunities for coordination between disparate stakeholders that might otherwise be overlooked.

Various missions and initiatives of OPSA address socio-economic challenges by drawing on scientific knowledge and being mindful of implementation realities and diverse stakeholder perspectives.

Strategic advisory through PM-STIAC

The Prime Minister's Science, Technology and Innovation Advisory Council (PM-STIAC) [9] represents OPSA's primary vehicle for systematic engagement with India's S&T ecosystem. Rather than offering any ad-hoc advice, PM-STIAC undertakes careful assessment of challenges and opportunities, and develops roadmaps that inform decision-making at the governmental level. The council serves as an advisory mechanism that balances scientific rigour and its scope with pragmatic policy prescriptions.

The One Health Mission of PM-STIAC recognised that human, animal, and environmental health systems function as interconnected networks rather than separate domains. This understanding informed approaches to pandemic preparedness and broader planning of health and nutrition security. Similarly, the National Quantum Mission buttresses India's engagement with quantum technologies, an area where fundamental research advances will translate into practical applications in computing, communication, and sensing systems, in near real time.

The PM-STIAC-led artificial intelligence initiative (India AI Mission) focuses on the advancement of national competitiveness in AI through the development of frameworks for the deployment of responsible and ethical AI across sectors. These efforts acknowledge the potential benefits of AI technologies and, at the same time, recognise the challenges in its implementation and associated ethical issues and societal impacts.

The Electric Vehicles (EV) Mission represents another area where scientific and technical knowledge informs policy development, supporting India's transition toward more sustainable transportation systems while recognising infrastructure, economic, and social factors that influence adoption patterns.

Synergy through ETG

The Empowered Technology Group (ETG) [10] extends OPSA's reach across the institutional landscape. It engages with ministries, industry representatives, research laboratories, public sector enterprises and functions as a coordination mechanism to align technological planning and investment decisions across agencies and sectors. Policy guidance through the ETG involves multidisciplinary analysis of technological opportunities and challenges. Rather than offering simple recommendations, the

group develops nuanced roadmaps that take cognisance of trade-offs, constraints of resources, aspects of indigenisation and complexities in their implementation. This effort comprises a review of current efforts by varied agencies and stakeholders to identify coordination needs to ensure that different initiatives complement rather than replicate.

Technology procurement and induction represent another key area of ETG activity. When significant investments in the technology space are under consideration, ETG evaluates and guides to ensure alignment between financial commitments and the strategic objectives. ETG also evaluates and creates synergies between agencies and identifies actions for self-reliance through innovative indigenisation.

STIAC activities show that, besides technical inputs, its advice now includes facilitation of sectoral mission planning, setting of collective priorities, and creating synergistic coordination among partnering agencies/institutions. By convening experts, policymakers, and practitioners for advice on shared goals, these mechanisms embed scientific expertise, both in the design and execution of policies and programmes. That said, it recognises that sustenance of their impact will require adaptive and agile governance structures, clearly defined accountability channels, and continued collaboration between government, academia, industry, and civil society. With these instruments in place, India now has an established and structured system and pathways to embed scientific evidence into policy, with provisions for continued assessment of their efficacy. This is expected to inform both the national priorities and international engagements.

Catalytic role of institutional science advice

Institutional science advice in India operates within a policy ecosystem where research priorities, funding mechanisms, and innovation pathways intersect at multiple junctures. In such a landscape, the OPSA functions as a catalytic node to integrate evidence-based insights with policies for societal development. Drawing on specific initiatives and their implementation, this discussion below explores how institutional science advice translates scientific evidence into policy outcomes and initiatives.

Role of Science Advice in Expanding Research Horizons:

By synthesising global trends and domestic capabilities, science advice identifies knowledge gaps and prioritises areas where an investment can yield optimum outcomes. It then guides the development of shared research infrastructures that enable diverse institutions to collaborate in synergy and ensure that research agendas are responsive to both the

science and translational opportunities at the cutting edge, and cater to the needs of varied stakeholders.

Expanding Access to Knowledge through One Nation One Subscription (ONOS) Initiative:

Researchers across India have long faced challenges in accessing scholarly publications and scientific literature, particularly in institutions with limited resources. The One Nation One Subscription (ONOS) initiative (proposed initially by an inter-academy group, [11, 12] is a response to remove these barriers. Through engagements with publishers and funding agencies, efforts were made to develop frameworks that broaden access to research resources and maintain sustainable models for knowledge distribution (Fig. 1). The approach recognises that scientific progress depends on equal opportunity access to the research community. It is, however, too early to assess the impact of these efforts, with their reach still being enlarged.

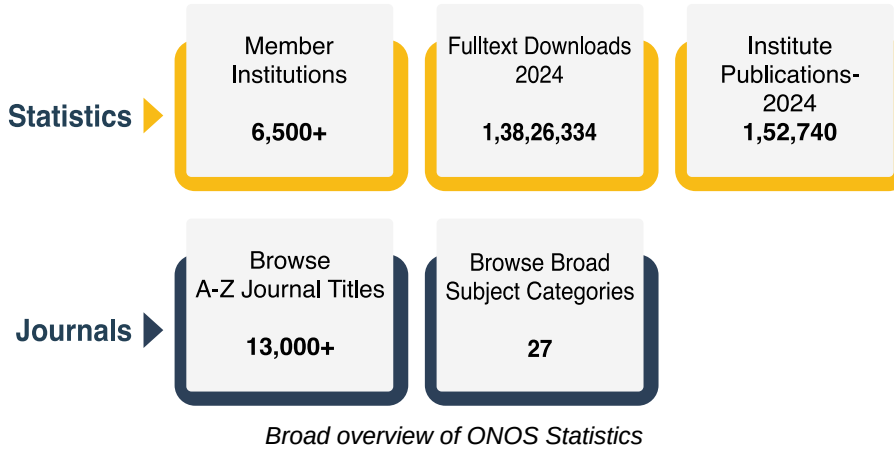


Figure 1: Broad Overview of Statistics during the first phase of ONOS (2025-27)

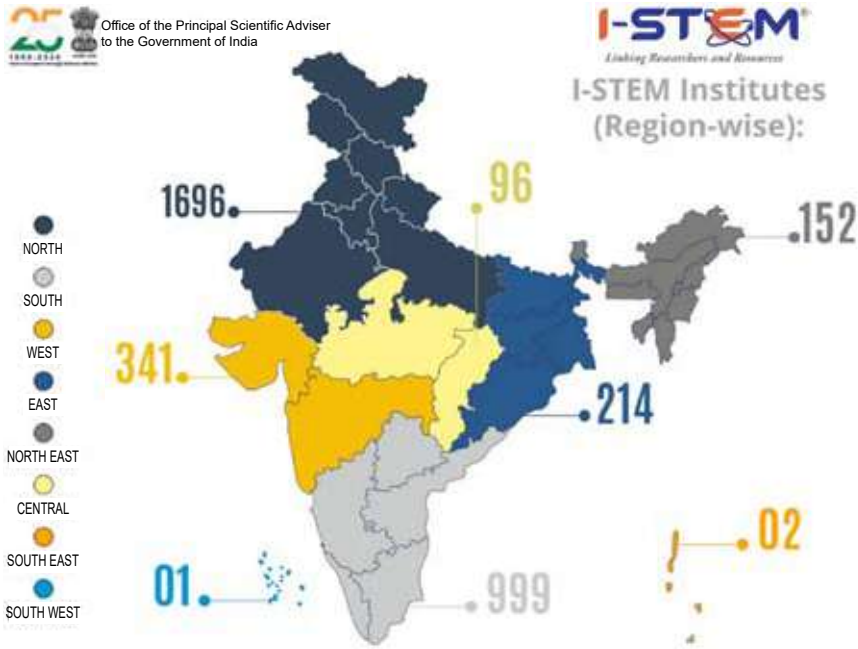
Research Governance through Anusandhan National Research Foundation (ANRF):

A recent review of research governance saw the creation of the Anusandhan National Research Foundation under the 2023 ANRF Act, with a five-year allocation of Rs 50,000 crore. ANRF is guided by an executive council [13]. This new framework aims to bring coherence to fragmented funding and priorities across sectors while maintaining scientific rigour. By bringing diverse funding streams under a single umbrella, this framework seeks to reduce duplication, foster strategic

alignment, and uphold scientific integrity across the national research landscape. With the vision of promoting translational research, the ANRF aims to build partnerships between Industry and academia, and therefore, to ensure effective participation and share of the industry and other non-government sources in investment in research, the ANRF envisages that over 60% of the total 50,000 crore will be provided by non-governmental sources [14].

Access to Scientific Infrastructure and Resources through I-STEM:

For long, research in India has been constrained by limited, invisible and uneven distribution of laboratory facilities. Recognising this, the Indian Science, Technology and Engineering Facilities Map (I-STEM) [15] portal was launched in 2020 as a gateway for researchers



I-STEM institutes are those facilities that have listed their scientific infrastructure on the portal, enabling wider access for the research community.

Figure 2: Illustration of I-STEM institutions across the country, mapped region-wise

and innovators to discover and access instruments across institutions. By uniting disparate laboratories behind a single portal and offering tailored support, such as priority booking for early-career and women scientists, I-STEM seeks to turn unseen and underutilised laboratory capacities into shared opportunities. Special initiatives within I-STEM promote

participation of women in science and engineering, provide platforms for collaboration, capacity development and technical support.

Science Advice in Ecosystem Facilitation:

Science advice fosters cohesive research and innovation ecosystems by mapping stakeholder strengths and recommending collaborative frameworks that bridge academia, industry, and government. Through guidance on partnership models and resource sharing, advisory inputs help establish incubators, clusters, and consortia that streamline technology transfer and amplify collective impact across sectors.

Shaping a Unified One Health Framework:

PM-STIAC conceptualised a comprehensive health security approach, recognising that emerging health challenges would require coordinated responses across stakeholders. The National One Health Mission [16] was approved by the government on 1st January 2024 and is coordinating efforts across twelve ministries and departments. OPSA held consultations between government agencies, private sector entities, multilateral organisations, and academic institutions (Fig. 3) to develop a framework for inter-ministerial coordination. The complexity of coordination across multiple agencies presents an ongoing challenge. The collaborative approach also extends to international forums, such as the G20 platforms, where such an integrated health security model contributes to global policies.

Innovation Networks and Partnerships through Manthan:

The Manthan platform [17] was developed to address gaps between knowledge generation and its translation into usable products. Operating through four pillars comprising opportunity creation, proposal submission, innovation exhibition, and collaborative meeting spaces, the platform has facilitated partnerships between government research organisations and industries, including collaborations in technology and other sectors. The aviation industry is one such success story.

OPSA's Strategic Alliance Division (SAD) extended this collaborative approach through targeted engagement with industry, foundations, academia, startups, and Micro, Small and Medium Enterprises for joint research and development through the establishment of Centres of Excellence by industry, but within academic institutions, and the development of innovative solutions for social challenges. An illustrious example of the success of this effort is empowering Science and Technology Clusters to facilitate the alignment of research endeavours with industrial partners, thereby enhancing collaboration and promoting the practical

application of innovative findings. And, such partnerships demonstrate the efficacy of scientific advisory mechanisms in creating value for stakeholders and in assisting national priorities.

Figure 3: Stakeholder agencies synergised for collective priority setting for the National One Health Mission

Demand-Driven Technological Innovation through RuTAG and RSVCs:

The Rural Technology Action Group (RuTAG) [18] and its associated Smart Village Centre initiative (RSVC) represent the demand-driven innovation approach. Established in 2004, RuTAG operates through seven IITs and focuses on identifying and addressing technology needs in rural areas. The recently launched RuTAG Smart Village Centres (now close to 50) provide platforms for testing and deploying technologies that address specific rural challenges, such as. The RSVC initiative was conceptualised to address the challenge of technology adoption in rural areas and aims to establish physical infrastructures that promote technology dissemination/education among rural communities, provides space for market linkage, carries out technology demonstrations and

helps entrepreneurship development (Fig. 4). The 12 technology tracks of RSVC address diverse rural challenges related to agriculture and waste management, renewable energy, fintech, livelihood and entrepreneurship, affordable housing, FinTech, capacity building, Government scheme apps, WASH, custom solutions and assistive technologies [19].

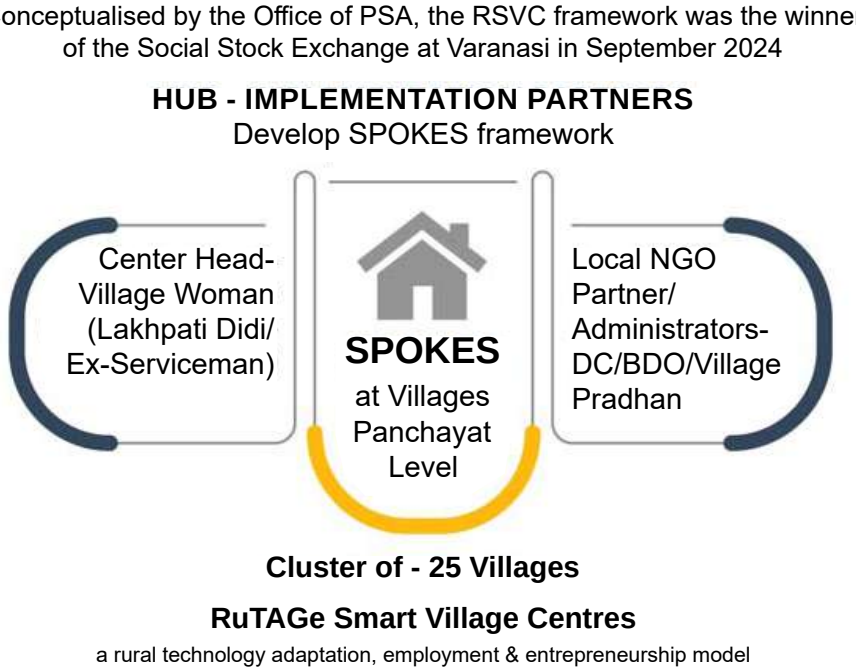

Conceptualised by the Office of PSA, the RSVC framework was the winner of the Social Stock Exchange at Varanasi in September 2024
HUB - IMPLEMENTATION PARTNERS
Develop SPOKES framework
Center Head-Village Woman (Lakhpati Didi/ Ex-Serviceman)
SPOKES
at Villages Panchayat Level
Local NGO Partner/ Administrators-DC/BDO/Village Pradhan
Cluster of - 25 Villages
RuTAGe Smart Village Centres
a rural technology adaptation, employment & entrepreneurship model

Figure 4: Hub and Spokes model by the RuTAG-RSVC initiative

RuTAG 2.0, launched in April 2023, focuses on commercialisation and broader dissemination of developed technologies. The initiative covers diverse sectors such as agriculture, textiles, energy, water conservation, healthcare, and livelihood enhancement. Through this approach, the aim is to ensure that practical solutions can be adopted at scale in rural communities.

S&T Clusters for Regional Development and Multi-Stakeholder Collaboration:

To encourage locally rooted solutions, OPSA has supported eight Science and Technology Clusters (S&T clusters) [20], where universities, startups, industry bodies, state governments, and international partners converge to address common challenges (Fig. 5). This shift toward place-based experimentation is guided by insights from PM-STIAC and expert groups, ensuring that regional pilots test solutions, like agri-tech in rural

areas and digital health in cities, to inform national policies without losing local relevance. Some of the notable outcomes of S&T clusters include the AR/VR-enabled artisan marketplace "Kalaanubhav.in," and the "One Delhi" digital transit app with over 3 lakh users.

Research and Innovation Circle of Hyderabad (RICH) in 2020
Vizag Science and Technology Cluster) in 2024
Jodhpur City Knowledge and Innovation Cluster (JCKIC) in 2020
PI-RAHI (Northern Region Science and Technology Cluster) in 2023
S & T Clusters
Pune Knowledge Cluster (PKC) in 2020
Bengaluru Science and Technology Cluster (BeST) in 2022
Delhi Research, Implementation, and Innovation (DRIV) in 2020
Bhubaneshwar City Knowledge Innovation Cluster (BCKIC) in 2021

Figure 5: The current eight Science and Technology (S&T) Clusters

Science Advice to Multi-ministerial and Multistakeholder Collectives and Prioritisation for National Missions:

In national missions, science-based advice plays a dual role through its contribution both to initial conceptualisation and mentorship during implementation. Thus, the role of PM-STIAC extends beyond traditional science advice to providing evidence-based input across ministries and stakeholders to ensuring strategic initiatives, while addressing practical implementation challenges. maintain scientific rigour (Fig. 6).

The National Quantum Mission (NQM) to bridge Scientific Ambition with Strategic Implementation:

Conceptualisation of the National Quantum Mission (NQM) [21] was one of the key missions discussed by PM-STIAC and involved a critical assessment of national competence in quantum technology and global developments. OPSA supported the establishment of four thematic hubs and coordinated between the Department of Science and Technology, academic institutions, and industry partners. The OPSA would ensure

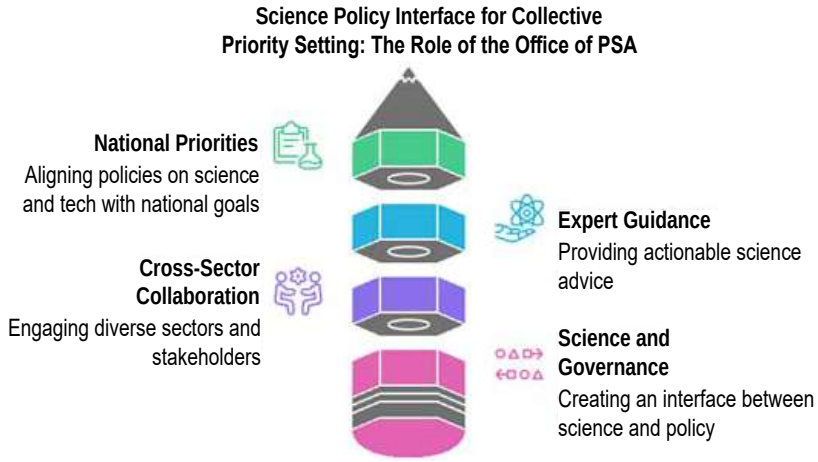

Science Policy Interface for Collective Priority Setting: The Role of the Office of PSA
National Priorities
Aligning policies on science and tech with national goals
Cross-Sector Collaboration
Engaging diverse sectors and stakeholders
Expert Guidance
Providing actionable science advice
Science and Governance
Creating an interface between science and policy

Figure 6: Illustration of how the science-policy interface plays a role in collective priority setting

that the mission's timeline is maintained, both in the advancement of scientific and technological development at a competent level and in meeting strategic objectives. It would also aim to identify translational possibilities.

The India AI Mission:

Identified as a national mission, the development of the India AI Mission involved a synthesis of inputs from and aspirations of multiple ministries, academic institutions, and industry partners towards the formulation of a national AI strategy. OPSAs' Science advice also helped develop the mission's seven pillars comprising computational capacity, foundational models, datasets, applications, and ethical frameworks to harmonise technical feasibility with societal needs.

The Government of India additionally constituted an advisory group for the development of an India-specific regulatory framework to deal with AI-specific issues. This is chaired by the PSA. A subcommittee on 'AI Governance and Guidelines Development' was formed to provide actionable recommendations for AI governance in India [22-24].

National Green Hydrogen Mission:

The mission aims to make India a global hub for green hydrogen production, use, and export, and its governance structure comprises an advisory and empowered group of technical experts on scientific and technological matters. The Mission Secretariat is nested in the Ministry of New and Renewable Energy, mandated with the implementation of

this program [25]. This arrangement ensures that scientific expertise remains integrated throughout the mission's execution while maintaining clear implementation accountability.

S & T for Sustainable Livelihoods and Socio-Economic Challenges:

The Mission for Science & Technology in Sustainable Livelihood Systems deals with the use of science-based advice for rural development through systematic consultation involving multiple agencies, such as the Department of Science & Technology, the Ministry of Rural Development, and the Ministry of Social Justice and Empowerment. Advisory input relates to the identification of convergence opportunities in agricultural research, rural technology development, and social empowerment domains [26].

Strengthening Global Partnerships:

This effort focuses on international collaboration by identifying national strengths in areas such as quantum technologies, AI, digital public infrastructure, clean energy, etc. and suggesting priority areas for joint initiatives on a global scale. OPSA's inputs guided the creation of bilateral and multilateral working groups, funding consortia, and an agreement on shared infrastructure for strategic and sustainable partnerships.

Towards a Global Science Advice Mechanism:

India's engagement with international science advisory networks has evolved into a platform for collaborative action. The G20 Chief Science Advisers' Roundtable [27], initiated under India's 2023 Presidency, has been carried forward with UNESCO. South Africa convened representatives from over 25 countries to compare advisory models, discuss open-access strategies, coordinate One Health responses, and anticipate emerging scientific and technological challenges. Beyond dialogue, follow-up working groups were established to develop joint roadmaps and conduct collaborative research in areas such as One Health and Inclusivity in STEMM (Science, Technology, Engineering, Mathematics, and Medicine). Some of these efforts have led to national-level framework building, taking inspiration from these multilateral consultations.

International partnerships:

The QUAD Centre for Quantum Information Sciences [28] is co-led by the Quad countries (United States, Australia, Japan and India). In

this, India is represented by the PSA. A report titled Quantum Science & Technology in the QUAD Nations: Landscape and Opportunities, discusses the key challenges identified by QUAD countries in Quantum Sciences, identifies areas with potential for collaboration, and outlines specific actions [29].

India's role in engagements such as the India-EU Trade and Technology Council's Green & Clean Energy working group and leadership of the Indo-US Quantum Coordination Mechanism under India-US TRUST (erstwhile iCET, the Initiative on Critical and Emerging Technology) translates discussions into targeted initiatives with measurable objectives, shared funding commitments with regular reviews of the progress.

Policy Frameworks and the Vision:

OPSA informs the design of policy frameworks through integration of foresight analyses, inclusivity principles, and sectoral priorities. By grounding policy design in evidence-based foresight and stakeholder diversity, science advice helps craft frameworks that are resilient, adaptive, and aligned with India's innovation goals. Some examples of such frameworks are given below.

India's Mega Science Vision:

The Mega Science Vision 2035 provides a strategic roadmap for the country's engagement with large-scale scientific endeavours over the next decade. These are centred on six critical domains viz., High Energy Physics, Nuclear Physics, Astronomy and Astrophysics, Accelerator Science and Technology, Climate Research and Ecology and Environmental Science, and this initiative seeks to strengthen India's scientific capacity through a SWOT assessment of national strengths, weaknesses, opportunities, and challenges [30]. Four Mega Science Vision 2035 reports have been released so far, outlining their scope as detailed below.

1. **Mega Science Vision-2035 High Energy Physics Report**: The report presents a priority-based plan to pursue Mega Science Projects in High Energy Physics to achieve international competitiveness along three frontiers, namely, energy, intensity, and the cosmic (astrophysical or cosmological observations).
2. **Mega Science Vision-2035 Nuclear Physics Report**: The report surveys the emerging scientific horizons of nuclear physics, measures the capabilities of the Indian nuclear physics community, and puts forward a plan for undertaking Mega Science Projects in Nuclear Physics in the time frame of 2020-35

3. **Mega Science Vision-2035 Astronomy & Astrophysics Report**: The report develops a roadmap for the Mega Science Projects in Astronomy & Astrophysics in India and makes a case for Indian participation in international projects for developing important projects.
4. **Mega Science Vision-2035 Accelerator S&T and Applications:** The report surveys the relevance of accelerators in terms of their application and puts forward a prioritised list of projects to be pursued during 2020 and 2035.

Deep Technology Innovation Ecosystem:

Deep technological innovation relates to innovations based on substantial scientific or engineering breakthroughs with the potential to disrupt conventional growth trajectories. Sectors such as defence, aerospace, energy, climate and agriculture, etc. would increasingly benefit from adoption of deep tech innovations in technology areas such as AI, Quantum, Drones, IoT and bioengineering. With the rapidly increasing number of deep-tech startups that pioneer solutions once dominated by international players, the support in the form of long-term and patient capital and a skilled talent pool can help make the deep-tech ecosystem future-ready. A policy exercise by OPSA through extensive stakeholder participation suggested the need for dedicated financial support which resulted in the announcement of Rs 10,000 crore Deep Tech Fund of Funds [31], along with efforts to create thematic regulatory sandboxes (a controlled micro environment that enable entrepreneurs to test innovative products, services, or business models under regulatory supervision), to foster innovations in emerging technologies. This exercise underscored the importance of a streamlined process for intellectual property and for a policy framework to ease technology transfer from the laboratories to the market.

Inclusivity in STEMM:

Recognition that diverse perspectives contribute to scientific progress has led to systematic approaches to inclusivity within India's science and technology ecosystem. OPSA's approach to inclusivity in Science, Technology, Engineering, Mathematics, and Medicine (STEMM) extends beyond demographic considerations and encompasses knowledge systems, linguistic diversity, and disciplinary perspectives. Through extensive public and expert consultations, a Self-Assessment and Reporting Framework on Inclusivity in STEMM has been developed to address challenges due to inadequate data across inclusivity indicators [32].

At a leadership-level meeting, the operationalisation of this framework in partnership with the Department of Higher Education (DHE), Capacity Building Commission (CBC), and All India Council for Technical Education (AICTE) was developed [33]. The effectiveness of this framework will depend on its adoption by institutions in letter and spirit to ensure a meaningful implementation. The efficacy of these initiatives will critically hinge on the ability to create a governance system to navigate through implementation challenges and the needs of diverse stakeholders.

Science Advice for Governance Capabilities

As India navigates through an increasingly complex technological landscape, OPSA has been developing capabilities that extend beyond traditional advisory functions to a system that identifies and prepares for emerging challenges and opportunities. This approach recognises that contemporary science governance requires frameworks that are nimble enough to identify interconnected issues, create systems to deal with them and prepare for associated technological change. The focus is on examining patterns across multiple domains to identify technological developments and policy inventions that may be needed. Towards this, the OPSA is building institutional capacity for systematic analysis of technological trajectories and their governance implications through steps like the International Technology Engagement Strategy for Quantum (ITES-Q) [34], released on the World Quantum Day of 2025.

The key focus of OPSA has been to make the Indian science firmament, future-ready in all respects, through a systems approach to identify critical and emerging technologies and social needs, recognising the relevant domains, including scientific, technological and social that would need integration, create systems for coordination in research, development, implementation, and help develop suitable governance structures.

The past experiences underscore the fact that a resilient science-policy interface must continually adapt to the evolving technoscientific landscape and, at the same time, uphold core principles of evidence-based policy and inclusivity. Past national as well as global experiences show that anchoring decision-making in sound science, encouraging dialogue, and safeguarding the integrity of information are key to navigating through technological and social disruptions and associated dilemmas in making educated, evidence-based decisions. The OPSA promises deeper convergence of science with policy goals, from driving innovations in emerging areas of quantum technology, green energy, and artificial intelligence to informing strategies on societal challenges like public health and climate change. There is an immense canvas, and the need is

to expand science advisory ecosystems at multiple levels of government and academia, such that even the state and local decision-makers also benefit from evidence-based scientific advice. It also aims to strengthen international collaborations through openness and willingness to share its resources for the global good. India is poised to evolve its science-policy interface in ways that science would catalyse its socio-economic transformation.

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Indian National Science Academy: Some Challenges Ahead[1]

Raghavendra Gadagkar

Scope

I am grateful for this opportunity to reflect on the role of the Indian National Science Academy (INSA) and its future, on the occasion of its 90th anniversary. It was my privilege and honour to serve as the President of INSA during 2014-2016. For me the short, three-year tenure as President was a great learning experience and will forever remain, a memorable experience in my life.

Truth be told, that part of my duty, which involved interacting with the government, was often challenging and at times frustrating. But the part which involved interacting with INSA staff, officers, council members and fellows, was always enjoyable and rewarding. Perhaps I had not hitherto realized, as to how remarkable our science academies really are. It is hard to imagine another kind of institution where nearly a thousand of the foremost experts in different disciplines, smilingly compete with each other to freely volunteer their time and offer their knowledge and skill in response to a simple request by email. The credit for establishing such a glorious tradition must go to the founders, successive presidents and office bearers of the academy, since its foundation in 1934. As the 37th President of INSA, I owed a debt of gratitude to a long and illustrious line of predecessors and of course to the entire fellowship. Among the few innovations we made during my tenure as President, the one I will cherish most and the one that I think will outlast everything else in its impact, is the establishment of the Indian National Young Academy of Science (INYAS). Rather than set out to describe in more detail all the wonder that INSA is, I seek your indulgence in permitting me to describe instead,

[1] Based on Presidential Remarks at the INSA Anniversary General Meeting, NISER, Bhubaneswar, 30th December 2016 and modified from Gadagkar, R. 2017. Guest Editorial: Indian National Science Academy: Some Challenges Ahead. Proceedings of the Indian National Science Academy, 83, 1–4.

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some important challenges that lie ahead for INSA. I will dwell briefly on what I believe are four important challenges namely, ethics and etiquette, inclusivity, policy advice, and social sciences and humanities.

Ethics and Etiquette

Election to the fellowship of INSA is both a coveted honour and a call for serving the scientific community. To maintain this exalted status, we must all adhere to the highest moral standards and follow an impeccable code of conduct. We are fortunate in having inherited the noble tradition that election is by nomination and not by self-application. But I am afraid we have not entirely realized the spirit of this tradition. To do so I believe that we must endeavour to take several steps. Ideally we must ensure that nominees are not even aware of their nomination, let alone have the opportunity and bad taste to lobby on their own behalf. Nominations are made by fellows of the academy — a proposer, a seconder and several supporters. We must insist that the proposer and seconder should be acknowledged experts in the field of research of the nominee. Either the proposer or the seconder should also be intimately familiar with the career path of the nominee. The supporters should either be reasonably familiar with the nominee or with the field of his or her research. It follows logically from all this that the proposer and not the nominee should fill-up the nomination form, summarize the contributions of the nominee and update the file where necessary. The office should not entertain direct correspondence with the nominee even to update their files. Let us face it - today none of these norms of etiquette and ethical standards are being observed by us. There is an urgent need to change the present 'normal' and 'accepted' standards of conducting our most important business, i.e., that of election of new fellows. After all, the alternative standards I am suggesting are indeed normal and accepted in the best science academies of the world.

Then there is the matter of conflict of interest. Today we do not deal with this issue satisfactorily. There are at least two deficiencies in our approach. First, we conflate conflict of interest arising out of close family ties such as one's spouse or relative being a candidate for election, and conflict of interest that is presumed to arise out of one's students or close colleagues being candidates. In both cases we ask the concerned member of the committee to declare such potential conflicts of interest and pledge to remain unbiased nevertheless. In the case of conflict of interest arising out of family ties, I think this is not adequate. The concerned member should, in my opinion, refrain from participation in the proceedings of the selection committee. In the case of one's students

or close professional colleagues, I personally do not consider this a conflict of interest. Indeed it would be very valuable to have a knowledgeable member of any committee who can provide much more authentic information and express much more informed opinion about the concerned candidate. My plea is that we should begin to believe that we can indeed behave like reasonable human beings. We should therefore encourage a tradition of honest, subjective evaluation by knowledgeable experts, rather than rely on blind, apparently objective numerical indicators.

Inclusivity

Like the rest of our society, Indian academia is stratified along multiple dimensions creating groups and subgroups with vastly different levels of visibility and opportunity but no clear variation in merit. Whether we are electing new fellows or conferring other forms of recognition, it is imperative that we do all that is humanly possible to avoid any bias based on such stratification. Nobody would disagree with this noble objective of achieving inclusivity. And yet it is very hard, perhaps impossible to achieve it in total. None-the-less, we should keep trying to approach the ideal end-goal even if only asymptotically. There are many axes along which there is potential for exclusion and inequality. Perhaps the most important of these is gender. Women continue to be grossly underrepresented in all our professional bodies. In INSA for example, we have at present only about 120 women out of a total of 1000 fellows. Needless to say, there are many complex, often inscrutable factors that contribute to this situation. Is there something that we can do without resorting to separate quotas for men and women? I am convinced that we can bring about a significant reversal in the skewed gender balance by redoubling our efforts to locate, identify, assess and nominate more and more women or other underrepresented groups (see below), rather than merely nominating those who first come to our attention and worse, those who proactively approach us with a request to nominate them. We receive only about 500 nominations per year from 1000 fellows. Clearly there is scope for fellows to take more interest and nominate outstanding candidates, both women and men.

Age presents a different kind of challenge. We are constantly endeavouring to bring down the average age of the fellowship. This is certainly a laudable goal but it need not come at the expense of ignoring highly deserving older nominees. It is adequate if we do not explicitly discriminate against young nominees on the grounds that they can wait, and with the sentiment that it is wrong to elect younger nominees while older nominees are still in the queue. We need to learn to use a judicious mix of promise and performance in our measures of merit.

There is a widely prevailing perception that nominees working in premier national research institutes have an undue advantage over those working in traditional universities. Whether or not this perception is based on reality, it is important for us to counter the perception. I believe that it is possible to do so by increasing our efforts to locate and nominate more individuals working in traditional universities. Neither women nor individuals working in traditional universities should go unrecognised simply because they are not so prominently visible to us.

Another contentious issue is that of interdisciplinarity. While we all extol the importance of doing interdisciplinary research, those who heed our advice often face a distinct disadvantage when they are assessed and compared with others who work within the confines of a single traditional discipline; their nominations are sometimes shunted between different 'reluctant' sectional committees. We urgently need to evolve procedures to overcome this problem and genuinely encourage interdisciplinary research.

Yet another kind of complication arises when we attempt to compare nominees who produce knowledge and publish papers or obtain patents on the one hand and those who participate in large technology missions of national importance. In the latter case, individual contributions cannot be measured or attributed in a simple way. It appears that such comparisons cannot be made by our existing sectional committee mechanism. INSA has recently established a separate search-cum-selection committee to overcome this problem. This committee also helps the academy to induct fellows in the areas of history and philosophy of science. This is a new experiment, and it has to be evaluated in the course of time and refined as necessary.

It is not so much a matter of fairness or a moral imperative to distribute fellowships uniformly. Instead, it is in the selfish interests of the academy, an imperative for our own good functioning, that we must aim to be inclusive, that we must endeavour to elect the best people available, be they men or women, young or old, situated in universities or national labs, working in any discipline or at the intersection between disciplines, producing knowledge or technology. Thus it is our collective responsibility to find ways and means to ensure that our existing rules and traditions are not used to exclude deserving individuals – merit should not be sacrificed at the altar of rules and traditions.

Policy Advice

An important function of the world's leading science academies is to provide their governments with well-conceived, evidence-based advice on all matters where science has a role to play. Indeed, the National

Academy of Sciences, USA was established "by an act of Congress, signed by President Abraham Lincoln in 1863" and is explicitly "charged with providing independent, objective advice to the nation on matters related to science and technology". INSA's history is rather different and we have to find clever ways of acquiring for ourselves an advisory role. It is generally true that our advice is not sought and when given, our advice is not necessarily heeded. It is easy to remain passive spectators of this ground reality and witness the gradual erosion of our relevance to society. But nothing prevents us from becoming proactive and voluntarily putting in the public domain a significant number of well-researched policy documents on a variety of subjects. Clearly, we have the expertise to do so, otherwise we would not be complaining that our advice is not being sought. The US government funds the US National Academy of Sciences only for the advice it provides them. But our government funds us even without demanding any advice, or anything else in return. In some ways we are in an even more fortunate position because we can choose the topics on which we would like to prepare policy documents. Consider the titles of the following small sample of the policy documents published by the National Research Council, a wing of the US National Academy that organizes the preparation and dissemination of their policy reports: *Developing Multimodal Therapies for Brain Disorders; Pathways To Urban Sustainability; Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors; Developing a 21st Century Global Library for Mathematical Research; Chemical Laboratory Safety and Security; Attribution of Extreme Weather Events in the Context of Climate Change; Exploring Strategies to Improve Cardiac Arrest Survival*. Are we really incapable of producing such reports? Let us seriously introspect and ask why we are not already doing so.

Social Sciences and Humanities

It is now widely recognized that there is unity of all knowledge, that the boundaries between natural science, social science & humanities are artificial and porous and that we cannot solve many of the world's problems today without integrating all forms of knowledge. I think it is superfluous for me to further elaborate these obvious facts. It follows then that we cannot give meaningful advice without such integration of different forms of knowledge across the natural sciences, social sciences and humanities. Unlike us, the best academies of the world make no distinction between scholars across these domains of knowledge and regularly elect scholars from a wide range of disciplines to their fellowship. By doing so and thus building an interactive community of multidisciplinary scholars, they are able to add value to the expertise available with practitioners of each discipline and thereby make their advice much more refined and

useful. Consider once again, the titles of the following small, sample of the policy documents published by the US National Academy of Sciences: *Deterrence and the Death Penalty; Priorities for Research to Reduce the Threat of Firearm-Related Violence; Confronting Commercial Sexual Exploitation and Sex Trafficking of Minors; Reforming Juvenile Justice; Implementing Juvenile Justice Reform; Parenting Matters — Supporting Parents of Children Ages 0-8; The Growth of Incarceration in the United States — Exploring Causes and Consequences*.

I recently had the privilege of watching the video recording of a lecture organized by the US National Academy of Sciences, by Mary C Waters, Professor of Sociology, Harvard University and a fellow of their academy, on "*The war on crime and the war on immigrants: new forms of legal exclusion and discrimination in the US*". Can anyone really believe that such reports can be produced without the close collaboration of scholars in the social sciences and humanities? How can INSA and Indian academia, even begin to address such challenges. These undeniably exist in our own environment, as we continue to insist on maintaining our misconceived 'purity' and treating the social sciences and humanities as untouchables? We have a rather strange and paradoxical attitude towards the social sciences and humanities. On one hand we maintain and cherish an ill-conceived air of superiority of the natural sciences and use this as an argument for not electing fellows in these important areas of scholarly knowledge. On the other hand we seem to harbour an unfounded fear of these disciplines. Unless we shed our notions of superiority and overcome our fears, we will continue to be perceived as irrelevant for solving real-life problems facing the society.

I have briefly outlined four challenges ahead for INSA namely, ethics and etiquette, inclusivity, policy advice and social sciences and humanities. In each of these areas we are not doing too well. But I refuse to believe that we cannot do better. I am an incurable optimist and my optimism makes me believe that INSA is up to this challenge.

I close these remarks by wishing INSA a very happy 90th birthday and a very bright future in the service of science.

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India's Rise in High Science – Led Innovation and Entrepreneurship

R.A. Mashelkar

Scope

This script describes the enormous possibility of deep science-driven innovation and entrepreneurship, which extends beyond laboratory breakthroughs and represents a pivotal avenue for establishing India's competitive advantage in the complexities of the 21st century. The essay emphasises a significant opportunity to cultivate a new generation of global leaders by harnessing a strong tripod of talent, technology, and trust with alignment of tax incentives, public-private partnerships (PPPs), technology readiness level (TRL) funding, and procurement reforms and the ASSURED framework—Affordable, Reliable, Secure, Universal, Responsible, Efficient, and Durable.

Historical perspective

When viewing India's journey in science, technology and innovation, it is useful to recall what Jayant Narlikar highlighted [1] in his book 'Scientific Edge' as the top ten achievements of Indian science in the 20th century.

In the pre-1950 era came Ramanujan's mathematical genius, Saha's ionisation equation, Bose's particle statistics, Raman's discovery of light scattering, and Ramachandran's structural biology. Post-1950, the list included nuclear power, the Green Revolution, the Indian space programme, high-temperature superconductivity, and the transformation of CSIR into an industry focused purpose-driven organisation.

Yet strikingly, none of these post-1950 achievements came from industry. They were mission-driven, government-funded endeavours. Unlike the US, Europe, China, or South Korea—where science-led companies like Google, Apple, Roche, BioNTech, Huawei, Samsung, and many others became global innovation leaders—India still lacks a comparable science-based enterprise which has made a global mark.

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Indian science-based innovation and entrepreneurship

Science provides the base for technology, which in turn triggers technology led innovation. It was the science of precise control of atoms in semiconductor materials that eventually led to the creation of microchips with billion transistors. It was the science of creation of single crystals of silicon carbide and gallium nitride that led to cell phone displays. It was the science of laser crystallization of amorphous silicon that led to flat panel displays. It was the science of hot electron injection in thin films of insulators that led to digital cameras.

Why is it that India has not done well in science-based innovation?

First, the journey from a scientific invention to socio-economic innovation can be complex and arduous. The fact that a nation does great science does not mean that it will automatically lead to great innovation. The Raman effect was discovered in India. But Raman scanner was created outside India. The iron-mercury-ion coherer, which formed the basic platform for wireless technology was created by Sir J.C. Bose, but the wireless technology is attributed to Marconi in Italy. In order to monetize the knowledge, one must 'own' that monetisable knowledge. It is not often recognized that it is not 'patenting or publishing'. It is 'patenting before publishing'. One can cite several cases of Indian science, leading to potentially monetisable knowledge. But that science was monetised by others outside India, not in India and by Indians.

Second, before 1991, in a protected economy, import substitution was the objective and, therefore, there was no incentive for creating new science-based products. The easy path was to copy the known products in the global market. First to the world product was a distant dream. So new science-based products did not get developed.

Third, the Indian intellectual property laws also led to this aversion to doing science-led innovation, even in areas which are strongly built on science, such as drugs and pharma, biotech, etc. For example, in the area of drugs and pharma, India became a leader in the production of generic drugs by copying the known molecules already researched and productionized elsewhere in the world. But once the patent laws, which recognized product patents were introduced in the year 2005, it led to several Indian drugs and pharma companies going for discovery research, or in other words science-led innovation to put new molecules, not just copies, into the marketplace. But even in 2025, that is we have hardly any new molecule in the market that are based on inventions in Indian pharma companies.

Fourth, it is only the 'monetisable' knowledge that is converted into money. When scientific breakthroughs take place, even to recognize that the new knowledge that is generated is monetisable, requires a special attribute of mind. Even when one has created monetisable knowledge, to convert it into money requires the presence of a robust innovation ecosystem. India has been sadly deficient so far but the ecosystem is improving slowly but surely.

The essential elements of a powerful national ecosystem comprise physical, intellectual and cultural constructs. Beyond mere research labs, it includes idea incubators, technology parks, a conducive intellectual property rights regime, balanced regulatory systems, strategically designed standards, academics who believe in not just 'publish or perish', but 'patent, publish and prosper', some scientists, who have the passion to become technopreneurs, potent inventor-investor engagement, 'ad-venture capital', and passionate innovation leaders.

Building a nation powered by high science-led innovation

For science-led innovation to truly flourish, we must create powerful incentives for those who generate monetisable knowledge. Today, our recognition systems largely celebrate excellence in pure science. This is vital – without frontier science there can be no breakthrough technologies. But equally, we must honour those who carry science across the last mile — into innovation that transforms industries and impacts society. India needs a new value system: one that gives esteem to science that solves, technology that transforms, and innovation that impacts.

Innovation is never a solo act. The journey from mind to marketplace is a symphony, not a solo performance. Yet our awards still privilege individuals. India must move towards celebrating teams – scientists, engineers, financiers, entrepreneurs – who together assemble the complex puzzle of innovation and deliver solutions that change lives.

Ideas must be nurtured, not left to chance. Every university and college cluster in India should host incubators, sector-specific innovation clusters, and Research & Technology Parks. These must bring together academia, industry, and finance in shared spaces where ideas can be tested, refined, and scaled. Encouragingly, India has already begun walking this path.

We must also build a conducive intellectual property regime. Traditionally, academic research has been public-interest-driven, while industrial R&D has served private good. The U.S. Bayh — Dole Act of 1980 transformed this divide by enabling patents from publicly funded research and allowing their licensing to private firms — reshaping the

innovation ecosystem. India too must design its own enabling regime that encourages translation without compromising public interest.

Regulatory frameworks must become facilitators, not bottlenecks. In life sciences, delays in approvals have driven companies abroad, depriving India of its cost advantage in clinical trials. In plant sciences, GM crop research remains stuck for want of a promotional yet precautionary approach. We must strengthen regulations so that they uphold the highest standards of safety (patient first) while also protecting India's comparative advantage (India first).

Financing is the lifeblood of innovation. Early-stage, risk-tolerant venture capital is indispensable for startups, yet India has long lacked such "ad-venture capital." Without it, brilliant ideas die before reaching maturity. Equally, government policies must seed early markets for science-based products — through tax incentives, excise duty relief, and large-scale public procurement, as China has successfully demonstrated. India must craft its own smart, intelligent support systems to accelerate new markets for indigenous innovations.

Above all, what India needs most is a new mindset – from the individual to the institutional to the national. We must shift from risk aversion to risk-taking, from cautious investors to daring ad-venture capitalists, from mistrust of public–private partnerships to trust-based collaborations. Only with such courage can India graduate from being a land of "first-to-India" products to a global leader of "first-to-the-world" innovations.

Especially the private sector must embrace this vision — not merely exploiting existing knowledge but investing boldly in creating new knowledge, new businesses, and new value. Science-led innovation is not just a pathway to prosperity — it is the only path that can secure India's rightful place on the global innovation map.

High Science based 'Innovation': Affordable Excellence

Predominantly we see three types of innovations in practice

The first is getting 'more from more for less and less people' (MML). For example, expensive high-tech technology is used to create products with increasing number of functions. Costs keep on rising and less and less people afford them. This makes inequality rise.

The second is getting 'less and less for more and more people' (LLM). Here, Jugaad products or knocked down low technology affordable products are developed, which are used by the resource poor people. This also makes inequality rise.

The third type of innovation is getting 'more from less for more and more people'. This means making high technology work for the poor. It also means that despite income inequality, we have access equality, creating a more equitable word.

This author spoke about the paradigm of 'more from less for more' (MLM) in 2008, in Canberra, in response to receiving an Australian Academy honour [2]. Subsequently C.K. Prahlad and this author wrote a paper in Harvard business review on how MLM paradigm help business doing well while doing good [3]. This was ranked among the top 10 must read innovation papers. This has been followed by the book, authored by this author with Sushil Borde. It is titled as 'More from Less for More: Innovation's Holy Grail [4].

Anand Mahindra's endorsement of the book sums it well *'More from Less for More is a visionary guide to creating a sustainable, equitable future. By challenging outdated paradigms, it offers a transformative strategy to ensure innovation benefits all, transcending boundaries. A powerful blueprint for shared prosperity and environmental integrity'.*

Indian Science has the competitive advantage of MLM

In science led innovation, it must be recognised that Indian science excels in doing MLM. The Table-1 shows this vividly.

Table 1

Country	GDP per capita (current US$), 2020	GDP (current US$ Trillions), 2020	R&D Expenditure (% of GDP)	R&D Spending (US$ Billions) in 2020	Publications Count, 2020	Publications Count per US$ Billion R&D Spending	Ratio of R&D US$ spent per R&D US$ Spent in India for same output (Round Numbers)
India	1,928	2.66	0.65%	17	1,67,157	9668	1
UK	41,125	2.76	1.70%	47	2,15,054	4583	2
Australia	51680	1.33	1.83	24	53,610	2203	4
China	10,435	14.72	2.14%	315	6,37,688	2024	5
Germany	46,208	3.85	3.13%	121	1,90,010	1577	6
USA	63,414	20.89	2.83%	591	8,07,027	1365	7
Japan	40,193	5.06	3.28%	166	1,31,706	794	12

The table below shows that India has the Highest R&D Publications Productivity per unit Dollar Spending among Leading Economies.

In short, Indian scientists have the advantage of creating high science-based products competitively at the lowest cost.

Some personal reflections on building innovation ecosystem

In 1989, this author took over as the Director of National Chemical Laboratory (NCL). The challenge then was that in those pre-liberalisation days, reverse engineering, copying or import substitution was the main research activity of Indian research laboratories as also the industry. Therefore, there was no taker for anything new and novel that was done for the first time in the world by risk averse Indian industry.

On the very first day after taking over, this author addressed entire NCL family and declared that from now on, National Chemical Laboratory will be International Chemical Laboratory exporting its knowledge through its international patents worldwide — even to leading multinationals [5]. This was quite audacious since in its entire history, NCL did not have a single international patent. We also changed the policy from 'publish or perish' to 'patent, publish and prosper'.

History was made when in early 1990s, NCL licensed three of its US patents on solid state polycondensation of polycarbonate to General Electric in USA, who was a leader with 40% market share in polycarbonate [6].

Licenses of NCL patents to other major multinationals followed demonstrating that our scientists were capable of generating patents of international class to enable reverse transfer of technology to the best in the world.

The journey of patent commercialisation continued when this author took over as the DG of CSIR in 1995. In 1996, CSIR became the first organisation to create a formal Intellectual Property Management Policy [7]. Monetary as well as promotional incentives for IPR licensing was a part of this policy. The IPR generation activity in CSIR grew exponentially.

In fact, in the year 2002, The World Intellectual Property Organization (WIPO) published the list of leaders in Patent Cooperation Treaty (PCT) filings in Asia. CSIR was number one followed by LG, Samsung and Huawei [8].

In the year 2004, this author had proposed the idea of scientist entrepreneurship, scientists to hold equity, knowledge as equity, setting up incubation centres, lab-industry mobility to the Government. After

five years, the Office Memorandum (OM) was issued on 25 May 2009 by Ministry of Science and Technology from which I am quoting below.

"The Government of India has approved the proposal of DSIR on Encouraging Development and Commercialization of Inventions and Innovations: A new Impetus. The key components of the proposal approved for implementation are:

1. Permitting the researchers to have an equity stake in scientific enterprises/spin offs while in professional employment with their research and academic organizations (universities, academic and research institutions, herein after referred to as Scientific Establishment);
2. Permitting the Scientific Establishments to invest the knowledge base as equity in the enterprises;
3. Encouraging the Scientific Establishments to set up incubation centers; and
4. Facilitating mobility of researchers between industry and scientific establishment.

The reflection in the foregoing is just to show a view from a personal window a two-decade journey of how brick by brick, the building of science-led innovation ecosystem based on strong IPR was built in CSIR, helping in turn other organisations (ICAR, DRDO, IISc, etc) industry also.

India at the threshold: Science-led innovation and entrepreneurship in the 2020s

But CSIR story is not the only story. India has made good progress in many ways, especially in the last decade or so. Here are some high points.

Startup India (2016) catalyzed a flourishing ecosystem. Until 2016, India had around 476 registered start-ups. By 2021, that number had surged to over 70,000. India went from producing one unicorn a year to one unicorn a week by 2021! Between 2015 and 2021, the country witnessed a 9x increase in investors, a 7x increase in start-up funding, and a 7x increase in incubators [9].

Today, India hosts over 159,000 DPIIT-recognized startups, making it the third largest globally, powered by more than 100 unicorns across fintech, health, EdTech, agritech, and more.

Atal Innovation Mission (AIM) under NITI Aayog shaped grassroots innovation. By 2025, 10,000 Atal Tinkering Labs across 35 states enable hands-on innovation for over 1.1 crore students; 72 Atal Incubation Centres are nurturing 3,500 startups and creating 32,000+ jobs [10].

Deep tech missions are now national imperatives:

National Quantum Mission (INR 6,000 crore, 2023–31), with thematic hubs and quantum infrastructure that position India among the top seven nations in quantum R&D [11]. India's first indigenous 25-qubit quantum computer, QpiAI-Indus, showcases homegrown quantum computing prowess. The semiconductor push – likened to mining "digital diamonds" – is real: India launched its first indigenous 32-bit chip at Semicon India 2025, stepping boldly towards chip self-reliance [12].

Space innovation is surging. The space regulator IN-SPACe launched an INR 500 crore fund for early-stage space technologies; an INR 1,000 crore VC fund for space startups followed; the ecosystem now houses 300+ space startups [13].

At the policy apex, the Anusandhan National Research Foundation (ANRF), born in 2023, replaced SERB and now centrally governs R&D direction, funding, innovation, translation, and infrastructure—with dedicated funds for innovation and industry transfer [14]. Budget 2024–25 created an INR 1 lakh crore corpus for innovation and startups, plus defense-deep-tech schemes; Vigyan Dhara funding ramped up steeply. These are not random acts — they form a tapestry: India is building innovation bridges from lab to market, from school to startup, from quantum to space.

Indian startups and science-led innovation

Indian academic incubators have begun translating research into impactful startups, showing that world-class science-led innovation can emerge locally. Let's look at a few select examples.

IIT Bombay's Society for Innovation & Entrepreneurship (SINE) [15] (established in 2000) has incubated 236 startups, raising INR 6,750 crore, valued at INR 27,000 crore, and filing ~300 patents. Successes include ideaForge (indigenous drones, 5th globally), ImmunoACT (affordable CAR-T therapy), Lifespark (Parkinson's assistive tech), HaystackAnalytics (genome TB diagnostics), Nano Carbon Florets (solar-to-thermal materials), and Gupshup, the first unicorn from an academic incubator.

IIT Madras Research Park [16] has nurtured ~280 startups, generating INR 1,600 crore in revenues and over INR 33,000 crore in valuations. The standouts are Uniphore (a $2.5B conversational AI unicorn), Ather Energy (e-scooters, $700–800M valuation), and Mindgrove (India's first high-performance RISC-V SoC chip).

Although we have hundreds of incubators, there are only a few that promote high science-based innovation. Among the leading ones are Venture Center (Pune) [17], C-CAMP (Bengaluru) [18] and FSID of IISC [19].

Just as an example, Venture Center (Pune) has the startup ExoCan (Exosome oncology platform), which is building diagnostics and therapeutics for cancer, which uses exosomes (nano-vesicles) as both diagnostic biomarkers and drug-delivery vehicles — a high-risk, high-reward translational biology platform (not a simple diagnostic kit).

OncoDiscover liquid biopsy technology to detect circulating tumour cells (CTCs) from a blood sample is another example. One of the rare technologies to get FDA approval in India, it has US patents and has also been introduced in US market.

C-CAMP (Bengaluru) has a startup Bugworks (novel antibiotic discovery — developing BWC0977 — a novel broad-spectrum antibiotic active vs critical WHO pathogens, the discovery of antibiotics with a novel mechanism of action, which has potential to bypass known resistance pathways.

Serigen Mediproducts and Rechargion are two spinoffs (out of eleven) from the National Chemical Laboratory (Pune), which have developed novel range of silk-based implants and high energy density sodium ion batteries. Both technologies are based on the high science that originated from the laboratory.

However, these are start-ups, which have been from top ranking institutions of India. However, there are startups, which have been bootstrapped and have had no institutional support and yet done high science led innovation. Some brilliant examples are the winners of the awards of Anjani Mashelkar Foundation [20], which awards breakthroughs that have moved from just copying best practice to creating next practice and creating products that represent affordable excellence at the same time. Here are a few that stand out.

Swaasa is an SaMD (Software as a Medical Device) innovation which performs screening of lung health for respiratory problems such as TB, asthma, pneumonia, COVID-19, interstitial lung disease, and lung cancer by using cough sounds as biomarkers. The patient can cough into a smart-phone, and the AI software offers real-time, inexpensive, accessible testing for respiratory diseases and can be operated with minimal training. The screening can be offered at as low as INR 1 per test at scale and is a great alternative to spirometry which is painful, expensive and inaccessible in remote regions.

The Swaasa team has published two articles [21, 22] in 'Nature' — one of the most premier scientific journals.

Axiostat is another breakthrough, an advanced wound dressing designed to stop profuse bleeding almost instantly. While standard gauze can take over 13 minutes, Axiostat achieves hemostasis in under two minutes. The innovation uses Chitosan, a unique biomaterial, in a novel sponge that forms a mechanical barrier at the bleeding site, effectively stopping blood loss — even in patients on blood thinners. Axiostat is now a US FDA cleared, CE marked and approved in 28+ countries. Today, Axiostat's applications extend beyond emergency and trauma to military, vascular, and surgical settings, with presence in 50+ countries.

The underlying science has been published [23] in a *Proceedings of the National Academy of Sciences (PNAS)* paper.

Such examples show how Indian start-ups are creating new science that gets published in world's topmost scientific journals like Nature, PNAS, etc.

But some challenges remain:

1. Many promising science-led ideas still struggle with translation to market, scaling, regulatory approvals, cost of manufacturing, etc.
2. Long development cycles and need for discipline in R&D vs business pressures continues.
3. Funding gap for deeper science (especially in middle/late phases) is bigger.

As a result, the proportion of deep tech startups in India is rather low (4%-12%). This needs to be boosted up. Draft National Deep Tech Startup Policy (NDTSP) from the office of the Principal Scientific Adviser to the Government of India has provided [24] a good analysis as well as a roadmap for enhancing this proportion.

Need to boost private sector R&D for science led innovation

A big challenge is that India's R&D investment remains ~0.7% of GDP. Out of this industry contributes only ~0.2%. These pales compared to China (7X), the UK (10X), the US (14X), and South Korea (19X). To close the gap, India must spur private R&D investment. Among many options, we focus on some major ones, namely Public-Private R&D partnerships and innovative public procurement systems.

Public-private R&D partnership programs

Public-private partnerships can drive sector-specific innovation, enable access to cutting-edge research facilities, and reduce risk for

companies, especially in high-risk areas by driving industry participation in national R&D efforts and bolstering India's position in the global innovation landscape. Here is just one example of the biggest public-private partnership that India has had so far [25, 26].

New Millennium Technology Leadership Initiatives [27] was launched by CSIR in 2001. Its mission was to drive India's global leadership in niche technologies by uniting public R&D, academia, and industry in a "Team India" effort. NMITLI targeted high-risk, pioneering technologies, initially providing modest funding and progressively increasing investment as technologies matured, and risks declined. It backed two types of projects: push initiatives, addressing national challenges, and pull projects, based on industry proposals.

To date, CSIR has led ~80 projects, involving ~420 partners, yielding ~40 new technologies and over 200 patents. Notable innovations include the e2o Plus electric car, PEMFC fuel cells, micro-PCR for diagnostics, Johne's Disease vaccine, and novel diabetes treatments, marking a transformative impact on India's innovation landscape.

NMITLI like public-private partnerships (PPPs) help distribute the financial and technical risks of high-cost R&D projects, making it more feasible for businesses to invest in uncertain or long-term R&D efforts. The U.S. Advanced Research Projects Agency-Energy (ARPA-E) program collaborates with private companies to advance high-risk, high-impact energy technologies. ARPA-E provides initial funding, reducing the financial burden on companies while encouraging breakthrough innovations.

Similarly, European Union's Horizon Europe program provides funding for public-private R&D partnerships in fields like AI and climate technologies, reducing risks and aligning private sector R&D with EU strategic goals.

India is experimenting with new PPP models such as setting up hydrogen valleys [28] which provide a platform for academic, start-ups and industry to co-innovate technologies from lab to market. We need more such initiatives.

Science-led innovation and public procurement policy

Public procurement in India in general has a tendency to opt for lowest cost (L1) and low risk solutions, and mature technology. Innovation is not routinely welcomed or rewarded. In part, this is due to the competing objectives and bureaucratic barriers that public procurers face, which discourage risk taking.

We must move away from this and create a bold, transparent and innovative public procurement policy [29]. The price for a lack of progressive public procurement policy can be heavy as we show in the example below.

How lack of progressive public procurement policy has hurt India

As an illustration, let's take the case of Simputer, a product of Indian innovation that was created almost two decades ago. Simputer was designed to be a low cost and portable alternative to PCs [30]. The idea was to create shared devices that permit truly simple and natural user interfaces based on sight, touch and audio. The Simputer was to read and speak in several Indian languages in its initial release. The Simputer prototypes were launched by the Simputer Trust on April 25th, 2001.

Simputer was hailed for its 'radical simplicity for universal access'. Before the arrival of the smart phone in 2003, Simputer had anticipated some breakthrough technologies that are now commonplace in mobile devices. One of them was the accelerometer, introduced to the rest of the world for the first time in the iPhone. The other was doodle on mail, the ability to write on a phone, that was later a major feature on the Samsung Galaxy phones.

Bruce Sterling writing in New York Times magazine had said, *"The most significant innovation in computer technology in 2001 was not Apple's gleaming titanium Powerbook G4 or Microsoft's Windows XP. It was the Simputer, a net-linked, radically simple portable computer, intended to bring the computer revolution to the third world...."*

Unfortunately, India missed bringing this computer revolution to the world because of a lack of progressive public procurement policy.

Designing Indian innovative Public Procurement Policy: Some fundamentals

Innovations are products of creative interaction of supply and demand. India has incentivized supply through creation of numerous national research and technology organizations that it funds. It has created schemes for part financing 'technology led businesses". Examples include NMITLI (described earlier), Biotechnology Industrial Research Assistance Council, Technology Development Board, etc. Various financial incentives, such as weighted tax deductions (now unfortunately withdrawn) have also been given to spur industry led supply of R&D.

Besides supply-side initiatives, we need aggressive demand side initiatives. With large procurement budgets, the Indian government

can not only be the biggest, but also the most influential and demanding customer.

The government approach could be based on three pillars.

First, government could act as the 'first buyer' and an 'early user' for small, innovative firms and manage the consequent risk thus providing the initial revenue and customer feedback they need to survive and refine their products and services so that they can later compete effectively in the global marketplace. (Interestingly, based on a survey of 1,100 innovative firms in Germany, it was found that public procurement is especially effective for smaller firms in regions under economic stress, a helpful lesson for India).

Second, government can set up regulations that can successfully drive innovation either indirectly through altering market structure and affecting the funds available for investment, or directly through boosting or limiting demand for particular products and services.

Third, government can set standards that can create market power by creating demand for innovation. Agreed standards will ensure that the risk taken by both early adopters and innovators is lower, thus increasing investment in innovation. The standards should be set at a demanding level of functionality without specifying which solution must be followed. By not prescribing a specific route, innovation is bound to flourish.

International experience shows that public procurement can be a powerful driver of innovation. Singapore's Government Procurement Programme gives local SMEs priority access to contracts, fostering R&D in tech and biotech. Finland's Innovation and Procurement Program enables high-tech SMEs to win initial contracts, boosting credibility for global expansion, especially in sustainable technologies. Japan guarantees contracts for R&D-intensive SMEs in robotics and electronics, reducing risk and ensuring steady revenue. South Korea's Public Procurement Service gives preference to technology-driven SMEs, supporting innovation-led growth. Across OECD nations, nearly 80% have introduced measures to promote innovation procurement, with 50% adopting action plans. The OECD's 2017 report, 'Public Procurement for Innovation: Good Practices & Strategies' captures these trends. In Europe, over one-third of companies have delivered innovative goods or services through procurement contracts since 2011.

But there is a welcome change on the horizon in India too. ideaForge could make progress as defence assured them order with an MoU/some advance [31]. Defence has separate start-up & technology development and commercialisation scheme called IDEX [32] under which they fund incubator at higher educational institutions like IITs and make buying

commitments. Even State governments (Maharashtra [33] and Kerala 34] are leading) are changing procurement rules for startups.

Indian public procurement policies will have to be based on the context of rapidly changing geo-political and geo-economic scenario.

How do we increase the success rate of science led Indian innovation

Innovation is a translation of a new idea into practice. Any innovation is considered as successful, when it is done with speed, it reaches scale, and it remains sustainably profitable and impactful over a long period of time.

The journey from mind to marketplace is an arduous process. But after entering marketplace, to remain successful in business over a long period is also challenging.

First consider the success rate of any idea into a success. An interesting analysis has been done by Stephen and Burley [35] in 1997 for Industrial Research Institute [14]. It lists out the significant odds that face the would-be innovators by analysing consistent data from new product development, potential activity and venture capital experience.

They show that there is a universal curve, which illustrates the number of substantial new product ideas surviving between each stage of the new product development process. It shows that out of 3000 raw ideas (handwritten), 300 are submitted, which lead to around 125 small projects, further leading to 9 significant developments, 4 major developments, 1.7 launches and 1 success.

In the book 'Leap Frogging to Pole Vaulting': Creating the Magic of Radical yet Sustainable Transformation' we had proposed a new framework ASSURED, which, if used proactively, can potentially increase, first, the chance of converting an idea into a business, and then remaining a successful business for a prolonged period [36].

A (Affordability) is required to create access for everyone across the economic pyramid, especially the bottom. S (Scalability) is required to make real impact by reaching out to every individual in the society, not a privileged few. S (Sustainability) is required in many contexts; environmental, economical and societal. U (Universal) implies user friendliness, so that the innovation can be used irrespective of the skill levels of an individual citizen. R (Rapid) means speed. Acceleration in inclusive growth cannot be achieved without speed of action matching speed of innovative thoughts. E (Excellence) in technology, product quality, service quality is required, not just for the elite few but for everyone in the society, since the rising aspirations of resource-poor

people must be fulfilled. D (Distinctive) is required, since one does not want to promote copycat, 'me too' products and services. In fact, we should raise our ambitions and make D as in 'disruptive', which will be truly game changing, as shown in examples below.

The table below provides summary of how ASSURED Total Innovation model has been leveraged by various stakeholders in the innovation ecosystem [37].

Stakeholder Use Cases	
Research Institutes	• Technology evaluation • Technology / innovation benchmarking • Decision support matrix for projects funding
Startups	• SWOT Analysis • Identifying probability of success • Formulating winning strategy
SMEs	• Identifying roadblocks for scaling up • formulating winning strategy
Corporates	• Identifying hot startups • Innovation/ tech scouting • Innovation portfolio management • Diagnostic tool for identifying commercialisation barriers
Investors (Angel/VCs)	• Promising startups for investment • Portfolio management • Decision support matrix for funding decision
Innovation Accelerators	• Funding decision tool • Identifying gaps in successful commercialisation
Government/Development Agencies	• Recognizing award worthy companies • Best practices identification
Industry Association/Foundations	• Innovation benchmarking • Best practices identification
Policy Makers/Think Tanks	• Public procurement policy

Strengthening IPR systems

In his book 'Reinventing India', Mashelkar has fully covered the aspects of protecting and prospecting of Indian knowledge systems [38]. The specific aspects of the third world challenges in IPR have been also covered by Mashelkar [39].

The good news is that India has witnessed a striking surge in patent activity over the past decade, with academic institutions and industry both emerging as drivers. Patent filings rose from 26,807 in 2014 to over 100,000 in 2024, making India the only top 20 country with uninterrupted annual growth. In 2023 alone, the Patent Office received 90,298 applications — 49,860 domestic and 40,438 foreign. Resident share grew from 24.8% in 2013 to 55.2% in 2023, the first time Indian

applicants outnumbered foreign ones. This reflects policy reforms, fee concessions, and growing IP awareness.

Patent grants grew 149% in 2023, the fastest global rate, with nearly 80% of processed applications approved. Contributions span firms like TCS (416 patents), to academic institutions like IIT Madras, which lifted grants from 19 in 2018 to 300 in 2023. Beyond IT, auto companies – Hero MotoCorp, TVS, Tata Motors – are filing strongly in EVs and autonomous mobility. While still behind China and the U.S. in volume and commercialization, India's rising domestic participation signals an encouraging innovation trajectory. But a lot more needs to be done to create Indian leadership in IPR.

IP asset management is being reshaped by AI, data-driven innovation, and emerging tech. CHAA authorship have intensified. At the same time, AI and ML are transforming IP operations—automating patent searches, infringement detection, and drafting with greater accuracy and lower cost. Blockchain is being explored for ownership records and smart licensing. Collectively, India's patent ecosystem must expand, while adapting to disruptive global trends.

The same is the case with technology transfer and licensing offices, which should be staffed with smart professional individuals They need to be incentivized suitably by linking their variable pay to their performance in successful technology transfer and licensing.

Harnessing the RDI scheme: A blueprint for India's innovation

How do we do the journey of concept to commercialisation with speed, scale and sustainability?

The current challenge could be understood in terms of the distinct stages of Technical Readiness Level (TRL), as it scales from TRL1 (concept) to TRL 9 (commercialisation).

We can consider three distinct stages.

1. First is TRL 1-3, which is an early-stage proof of concept research;
2. Second is TRL 4-6, which is a development stage, comprising prototype development and simulated environmental pilot;
3. Third is TRL 7-9, which is the commercialisation stage, comprising demonstration, testing, evaluation and successful deployment in market.

All the current GOI R&D support schemes (by CSIR, DBT, DST, MeitY, etc.) support low level TRL (1-3), very few helping in TRL (4-6) and none at all in the crucial higher level TRL (7-9) that leads to final market validation and commercialisation.

The Government's new Research, Development, and Innovation (RDI) Scheme [40], with an unprecedented allocation of INR 1 trillion, offers a moonshot opportunity to secure India's innovation sovereignty. Approved in July 2025, with INR 20,000 crore earmarked in Budget 2025-26, it is the largest targeted R&D fund in India's history—designed to spur private-sector R&D across sectors like energy security, AI, biotech, quantum, digital economy, and national security.

The scheme is modelled on the "Fund of Funds" approach, offering concessional long-term loans and equity (not grants) for projects at TRL 4 and above. Funds will flow from the ANRF's Special Purpose Fund to second-level managers (AIFs, DFIs/NBFCs, research parks). Financing will cover up to 50% of project costs, with flexibility for higher support in exceptional cases. DST will oversee implementation, backed by ANRF and an Empowered Group of Secretaries, after consulting 10,000+ stakeholders.

The scheme should target TRL 4–6, bridging India's "valley of death" between lab ideas and prototypes. Global lessons abound—Germany's Fraunhofer Institutes, UK's Catapult, US's DARPA, and joint firm-academia labs. At least 15% of funds should go to mid-sized firms and startups, with challenge-based funding for national priorities such as clean energy, affordable healthcare, and quantum hardware. Blended financing with VC, CSR, philanthropy or state deep-tech funds can accelerate scale-up, while accredited testbeds can reduce risk. ASSURED framework described earlier should be used to assure the success at each stage. New PPP platforms will be needed to enable co-development of technologies and navigating them through the valley of death.

Accountability is critical. Global models show the way—South Korea tied R&D support to exports; Finland's Tekes measured global competitiveness. India should adopt transparent metrics (R&D intensity, patents filed, deep-tech products launched, jobs created) and commission independent audits. Annual public reports can build trust, with national targets—for example, enabling 100 Indian firms to match global peers in R&D intensity within five years.

Done well, the RDI scheme will not be another subsidy but a transformative bet—propelling Indian firms, startups, and researchers into the league of global innovation leaders.

The way forward

In his paper titled 'what will it take for Indian science, technology and innovation to make a global impact', Mashelkar [41] has provided a

broad roadmap. But the present essay is essentially focused on science-led innovation and entrepreneurship.

If India leverages its great tripod of talent, technology & trust, aligns tax credits, PPPs, TRL funding, and procurement reform with the ASSURED framework, we can truly create global leaders. Science-led innovation need not stop at lab breakthroughs—it can define India's competitive edge in the 21st century.

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Dr Mashelkar has also held esteemed positions within the scientific community, serving as the President of the Indian National Science Academy (INSA), the Institution of Chemical Engineers (UK), and the Global Research Alliance.

The Role of Science, Technology and Innovation in India's Journey as an Independent Country

Shekhar C. Mande

Scope

Science, Technology and Innovation form the backbone of human development. Indian history is rich with examples where one observes the confluence of these in making human life easier. Immediately after gaining independence in 1947, India's scientific community began using Science, Technology and Innovation as the engine of country's development thereby attempting to gain its rightful place in the world order. Results of these have been spectacular. In recent times, new challenges have emerged for humanity, and it is reassuring that India's scientific community is well equipped to deal with these challenges. Some examples of India's journey are highlighted in this essay.

Role of science, technology and innovation in economic growth

"*Is it not a curious fact that in a world steeped in irrational hatreds which threaten civilization itself, men and women-old and young-detach themselves wholly or partly from the angry current of daily life to devote themselves to the cultivation of beauty, to the extension of knowledge, to the cure of disease, to the amelioration of suffering, just as though fanatics were not simultaneously engaged in spreading pain, ugliness, and suffering*?" wrote Abraham Flexner in his classical 1939 essay, *Usefulness of Useless Knowledge*. This sentence indeed captures the essence of fundamental scientific discoveries, advancement of knowledge, the very beauty of science, all at once, at the same time alluding to its applications for the benefit of the mankind. That science and technology have been **primary drivers of human development** throughout history, having transformed how

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we live, work, and relate to each other, has never been in question. But only now it has been formally recognized in the 2025 Sveriges Riksbank Prize in Economic Sciences in memory of Alfred Nobel to Joel Mokyr, Philippe Aghione and Peter Howitt.

The industrial revolution was a phase of significant acceleration in the economic growth of Europe and some other parts of the world and besides an economic transformation this was also a period of **revolution in science, technology and innovation.** It fundamentally changed the manner in which humans harnessed **energy, materials, and knowledge** to produce good and organize societies. However, India's growth in the first 100 years of industrial revolution lacked similar momentum due to colonial occupation.

Consequently, when India earned the rights of self-governance in 1947, the overall developmental parameters were abysmal compared to the developed countries. Moreover, two catastrophic events had drained the country of its economic resources, namely, the Bengal famine of 1943, and the massive human migration in 1947, bringing the country on the brink of a humanitarian disaster. Although, both these events were largely man-made, economic activity of the country immediately after its independence was significantly devoted towards mitigation of these incidences. It is therefore not surprising that post-independence, S, T & I were adopted for the progress of Indian society. Consistent policies in science and technology over the last 78 years have transformed India from a resource-dependent colony into a global knowledge economy. India now proudly ranks among the top 5 countries as far as the GDP is concerned.

Science prior to India's independence

Prior to the independence in 1947, India had outstanding examples of scientists pursuing their passion, either through their own means, or through generous support by philanthropists. Examples of philanthropy and the outstanding science that emerged, included C.V. Raman with support from Amrit Lal Sircar and G.D. Birla and J.C. Bose with support from Sister Nivedita and Sara Chapman Bull and others. But yet, strong sustained support from public funding was reserved for much later days. Nonetheless passionate efforts of the individuals backed up by a handful of philanthropists, yielded some outstanding results that gained international acclaim.

Initiation of scientific institutions

Public funding for science and technology, and significant support from the Government in India can be traced to the origin of the Council

of Scientific and Industrial Research (CSIR) in 1942. Prior to the establishment of CSIR, other organizations with the Government support included, the Survey of India (est. 1767), India Meteorological Department (1875), Indian Research Fund Association (1911)- later renamed as the Indian Council of Medical Research, the Geological Survey of India etc. However, as a large organization spanning multiple fields of S & T, supported primarily through public funds, the foundation of CSIR was a landmark step.

It is not surprising that CSIR received enthusiastic support from private organizations from its beginnings. Its first Director General, Shanti Swarup Bhatnagar had worked closely with Industry for his own research during his early career. Bhatnagar was approached then at the Punjab University by Messrs Steel Brothers and Co. London to solve a problem that the industry was facing. Bhatnagar was able to address the problem and solve it to the satisfaction of the company. As a reciprocal measure, the company compensated the intellectual efforts of Bhatnagar and his colleagues with a generous financial donation. Consequently, Bhatnagar, while setting up CSIR, was fully aware of the role that industries can play in scaling up the technological innovations of scientific laboratories. Therefore in the subsequent years, he ensured that industrial houses remained close in contact with the CSIR.

In the making of modern India, especially post-independence, multiple industrial houses played an important role in the establishment of S, T & I organizations in the country. For example, Khwaja Abdul Hamied, along with Arcot Ramaswamy Mudaliar, had persuasively followed with the British for the initiation of CSIR. Hamied had already established a successful Pharmaceutical industry, the Chemical, Industrial and Pharmaceutical Laboratories (CIPLA). His deep interest in the formation of CSIR showed a strong intent from the industry to be involved in India's S, T & I ecosystem. Similarly, from the very beginnings, the Tata industrial house also supported many S & T organizations such as, CSIR, Indian Institute of Science, Tata Institute of Fundamental Research (TIFR) and others. Substantial support from the house of Tata's allowed CSIR to start the National Chemical Laboratory, Pune and the National Metallurgical Laboratory (NML), Jamshedpur. NML continued to work closely with the Tata Iron and Steel Company (TISCO)- now Tata Steel Ltd., for problems related to the industries. Moreover, JRD Tata attempted an interesting exercise of raising money through appeal to the general public, what today is termed as crowd-sourcing. With the appeal from JRD Tata, a total of Rs. 44,000, much of it contributed from the mercantile association of Calcutta, could be raised as a donation to

CSIR. Thus, a strong industrial support was ingrained in India's journey of S, T & I from its early years.

Post-independent era witnessed many new institutions being established for specialized human resource development. This included, setting up of the Indian Institutes of Technologies, All India Institute of Medical Sciences, New Delhi, many new Central Universities, and a large number of State Universities and more recently the Indian Institutes of Science, Education and Research. New ministries and departments within the Government also started, specifically to address different disciplines of modern S, T & I. These included Department of Atomic Energy, Department of Space, Department of Science and Technology and others. Thus, the entire eco-system for promotion of S, T & I was created and has functioned with great distinction since then.

Post-independence growth of the country through S, T & I

India, lagging in economic and humanitarian growth during colonial occupation, had many challenges of extraordinary magnitude to meet at the time of independence in 1947. The challenges existed on all fronts of societal growth. Production of sufficient food to feed her people, employment for a very large unemployed population, implementation of democracy, creation of an industrial base, implementation of strong educational sector, were among the many matters which needed urgent attention. With the application of science and technology, many of the challenges began to be addressed. A few of the examples of the same are discussed below.

Despite the economic hardships during the early years immediately after independence, many scientists took upon themselves to start the process of nation building through S, T & I. There are several examples in the early years of independent country, or the immediate years preceding. This included the work of P.C. Mahalanobis, who initiated sample surveys on multiple topics such as consumer expenditure, public opinion, plant disease, etc. His work along with C.R. Rao, D.N. Majumdar and others on the large Bengal Anthropometric survey, and the statistical analyses that followed, remains a benchmark contribution in the history of science. Such surveys would be useful not only for forming policies, but also formed a strong rational basis for implementation of developmental work in a planned phase. Importantly, their effort established that large surveys could be undertaken and the outcomes of these could be analysed meaningfully. Moreover, the work also eventually led to development of novel statistical methods for future analyses. C.R. Rao's seminal work during 1944-49, now known as Rao-Cramer inequality and Rao-Blackwell theorem are now being taught at undergraduate level around the world.

The work done in Kolkata was concurrent with that of Blackwell and Cramer in the western world and remains one of the outstanding examples of scientific contributions from modern India.

Examples such as that of the green revolution starting mid-1960's are well known in the public domain. Such examples were characterized by strong political support led by C. Subramaniam, who was then the Union Agriculture Minister, proactive bureaucracy led by B. Sivaraman and appropriate technological interventions. But the symphony of agricultural scientists led by M.S. Swaminathan, chemical industries, scientists working on mechanization of agriculture led by Man Mohan Suri, irrigation engineers, all working in tandem, is an outstanding example for posterity. The spin-offs of industries from scientific laboratories (for example Punjab Tractors Ltd from Central Mechanical Engineering Research Institute) in the process of the revolution also highlights the role of industry working in close collaboration with a scientific laboratory for the larger goal of development. The green revolution in India indeed remains among the most noticeable examples of modern times and a true triumph of science and technology.

In the healthcare front, an example of a seasonal disease, which accounted for large mortality, was cholera. The cholera pandemic between 1817 and 1824 itself is reported to have accounted for more than 8 million deaths in India. Although the organism causing cholera, later named as *Vibrio cholera*, had been identified earlier by Filippo Pacini in Italy, and later confirmed by microscopic visualization and confirmation of its microbial source by Robert Koch in Kolkata, the cause of clinical manifestation became apparent much later through the elegant work of Sambunath De in 1959. The discovery of cholera toxin carried out at the Nilratan Sircar Medical College, Kolkata by Sambunath De, and its cellular effects elucidated later, remains an example of classical microbiological work. Similarly, Dilip Mahalanabis's work on oral rehydration therapy for cholera is estimated to have saved millions of lives, and possibly avoided a pandemic-like situation in the aftermath of massive migrations post 1970. Thus, post-independence, research work was initiated in India to understand communicable diseases afflicting Indian population and to come up with remedies to overcome them. Due largely to such efforts, combined with improved sanitation, vaccination and other measures, India has made a substantial progress in reducing the burden of communicable diseases in the last 78 years. An INSA publication, Indian Science Transforming India, 2018, provides several examples of Science in providing critical solution for the benefit of the society.

Challenges for the future

India's economic progress in the last 78 years has largely been fuelled by synergistic collaborations among the policy makers, industries and scientists. There are no two opinions that S, T & I has played a central role in this journey. However, despite the achieved progress, there are many significant challenges which still remain, apart from new challenges which have emerged. The issues arising out of burgeoning urban population, agricultural productivity, rapidly depleting water resources, shift in focus of public health from communicable to non-communicable diseases, issues related to civic infrastructure, all needing urgent attention. However, all of these can be addressed effectively by proper applications of science and technology. More importantly, these need adequate support from the policy makers, industry and society, just as has been observed in the last 78 years.

There are also emerging matters that are causing global transformation and warrant urgent attention. After two centuries of progress, powered by **science and technology**, humanity now paradoxically faces **issues** *caused* by that same progress: **climate change**, threatening ecological and economic stability and **artificial intelligence (AI)**. All of these are capable of disrupting the very foundations of work, ethics, and governance. While solutions to some of these are unlikely to arise in the immediate future, there is a need to have continuous deliberations among civil society and the scientific fraternity. There is little doubt that India's S, T & I community is capable of addressing these in the coming years. But for this to happen, continued strong support to fundamental curiosity-driven science and its applications for addressing local issues would be needed. Indeed, Science, Technology and Innovation hold the key to India's successful transition into a developed country in the coming times.

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His academic contributions have been in the area of structure-function relationships of proteins, mostly derived from Mycobacterium tuberculosis. He has also contributed to development of computational methodologies for analysis of large biological data. He has been recognized by election to the three science academies in the country, Indian National Science Academy, New Delhi; Indian Academy of Sciences, Bengaluru and National Academy of Sciences, India, Allahabad and the Shanti Swarup Bhatnagar Award in Biological Sciences in 2005. He was recently awarded the Distinguished Alumnus award of the Indian Institute of Science, Bangalore.

Currently, he occupies Distinguished Professorship at the Bioinformatics Centre, Savitribai Phule Pune University (formerly University of Pune) funded generously by philanthropic donation by Dr. Anand Deshpande. He also serves on the board of Tata Steel Ltd. as an independent director and chairs the board of the Biotechnology Consortium India Ltd. He also chairs the governing board of the National Council of Science Museums, and is the National President of Vijnana Bharati, a large voluntary movement for Science with Swadeshi spirit. He is the President-elect of the Indian National Science Academy, New Delhi.

Overcoming Challenges of Doing Science in India: A Personal Perspective

Samir K. Brahmachari[1]*

Scope

Science in India has thrived against odds and developed due to individual and collective dreams, passions, perseverance and strategic ingenuity with minimal resources. The article showcases that when leaders dream beyond constraints, nurture young minds, and align curiosity with national purpose, world-class science becomes possible anywhere. The importance of institutional ecosystems, exposure of young minds to the frontiers of science, and a visionary administrative support is highlighted. This "toolbox" offers suggestions for young scientists and policymakers alike to dream audaciously, invest in mentorship and teamwork, democratize technology, build flexible network of institutions and support it with enabling administrative firmament, that facilitates new science and translation of such discoveries into societal good. Success in science lies in the joy of the journey with both passion and compassion, not only in reaching the destination.

Introduction

Over the past five decades, the way of doing science has gone through a major changes, especially in the biological sciences. The advent of molecular biology and the completion of the Human Genome Project have redefined both the scale and the spirit of enquiry. During this period, the Indian economy and science landscape have also undergone a phenomenal change. It transformed from individual excellence under resource constraints, import substitution and economic sanctions to technological leadership. One thing that has not changed is the need to

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ask the most appropriate questions and the innate desire to synergistically pursue both individual and collective dreams.

The scientific enterprise has moved from a single principal investigator (PI) driven small laboratory initiative (Science1.0) to mega science, involving many laboratories and diverse expertise, like the Human Genome Project, or the Indian Genome Variation Project (Science 2.0) to the crowdsourcing of knowledge and expertise for projects like Mapping the Human Brain or Open-Source Drug Discovery (OSDD, Science 3.0). We now stand at the threshold of new frontiers (Science 4.0) wherein AI driven tools like Alpha fold 2.0, Chat GPT 5.0 and Google Gemini or IBM Watson will be a part of the research team. We have also entered an era when Nobel Prizes in science, especially in life sciences are shared by scientists for their work done in commercial companies and startups.

This article presents a personal perspective of the author who has been a practitioner and a keen observer of Indian science for over five decades. The key learnings are:

"Dream big, pursue your dream with passion and rest will fall in place".

"Scientific aspirations should exceed the available resources, expertise and technologies".

Science 1.0: In the pursuit of excellence: Building institution, building people

Historically and under the British rule, science was popular in the eastern and southern parts of India and it thrived largely as an individual enterprise. During this era, the nation produced eminent physicists, mathematicians, chemists and clinicians. After a clarion call from visionaries like Shanti Swarup Bhatnagar, Homi Bhabha, Vikram Sarabhai and others, organized science developed and was branded as government science. With the exception of a few institutions, individual-driven science took a back seat. Even under such conditions, excellent individuals in a passionate pursuit of science created their own ecosystems akin in a manner that a silkworm does for itself. The present Indian science and technology ecosystem is the outcome of dreams of a few individuals' and due to governmental support in post independent India [1]. It is noteworthy that the India's first national science institute for fundamental research in basic sciences, the Indian Association for the Cultivation of Science (IACS), was established in Calcutta in 1876 by a private medical practitioner called Mahendralal Sarkar. And, it was here that C.V. Raman did his Nobel Prize winning work.

The Indian Institute of Science (IISc) at Bangalore was established with the support of Sir Jamsetji Nusserwanji Tata in 1908. The subsequent establishment of national laboratories under the Council for Scientific and Industrial Research (CSIR) by Shanti Swarup Bhatnagar during 1946 to 1956 had a substantive support from the Tata Industries. It was this visionary legacy of Jamsetji Tata, carried forward by Dorabji Tata and J.R.D. Tata, that helped create the first set of modern temples of science and technology for independent India.

IISc was dedicated to the pursuit of scientific excellence and to creating future leaders of Indian science. Even after 117 years, IISc still remains the most acclaimed institute for scientific research and education in India. Under the visionary leadership of Satish Dhawan, IISc could attract two of the best minds of Indian science — G.N. Ramachandran (GNR) and C.N.R. Rao (CNR) to establish two world class centers of scientific excellence, Molecular Biophysics Unit (MBU) in 1971 and Solid-State Structural Chemistry Unit (SSCU) in 1976, respectively. The author was fortunate to join MBU in 1974 as a JRF in a CSIR-funded project to GNR and in the following year, he enrolled as a PhD student. He eventually became a Professor at MBU before moving to Delhi in 1997 to establish the CSIR–Institute of Genomics and Integrative Biology (CSIR-IGIB).

It was the influence of GNR and CNR, who singularly focused on scientific excellence, that left a large and sustained legacy of generations of scientists in structural biology and solid-state chemistry. In these areas of research, the Indian scientific contribution is globally recognized. For the author, as a young faculty at IISc, their examples fortified a conviction that world class research in both theoretical and experimental sciences could be done in India, even when the resources were scarce.

Global footprint of structural biology: Biology meets computation

The discovery of triple helical structure of collagen by GNR in 1954 at Madras University could be marked as the first global footprint of post independent Indian Science in Structural Biology. The subsequent discovery of the Ramachandran Map by GNR, C. Ramakrishnan and V. Sasisekharan in 1963 could be considered as the most important fundamental discovery in structural biology from India. GNR moved to IISc in 1971 to establish the MBU. The word unit was considered by GNR to emphasize a small group of researchers and not a department. All the faculty of the unit focused on exploring the structure-function of biopolymers (polypeptides, polynucleotides and polysaccharides) using conformational analysis, X-ray crystallography, biophysical chemistry, peptides and oligonucleotides synthesis, protein biochemistry

and molecular biology. Over the next two decades, under the leadership of V. Sasisekharan, MBU became a globally recognized center in Structural Biology. Some of the landmark discoveries here, included the elucidation of the role of hydroxyproline in stabilization of triple helical structure of collagen, the first X-ray structure of type -II beta turn in a linear peptide as proposed by GNR and C.M. Venkatachalam in 1968, the first crystal structure of protein and virus from India, and the structure of peptides with unusual amino acids.

At MBU, questioning established dogma was not a taboo. During the mid-70's, Sasisekharan used a systematic approach to develop a conformational framework for polynucleotide structures to propose that a DNA can have alternate structures other than right-handed double helix. He then proposed sequence dependent left-handed DNA structures in 1978 and the left-handed Z DNA structure was discovered in 1979 in an oligonucleotide crystal by Alexander Rich at MIT. This work created a global impact and provided an impetus for a renewed interest in the study of DNA structures. It was amidst this group in the early 80's, as a young faculty, that the author could establish a vibrant environment to examine the functions of sequence dependent alternate DNA structures both *in vitro* and *in vivo*, and in questioning the idea that repetitive DNA sequences in the genomes are junk and unlikely to have any function.

It is gratifying that the Indian contribution in solving telomere and other unusual DNA structures and role of repetitive DNA sequences in biological function was globally acclaimed and today repetitive DNA occupies the center stage for understanding biological regulation. This demonstrates that a single PI driven initiative in an unchartered path and with limited resources could give rich academic dividends. The development of leadership in structural biology across the institutions in India over the last five decades can be traced back to GNR School at MBU. The story of MBU is well documented by Hari Pulakkat in his book "Space Life Matter": The coming-of-age of Indian science.

Science 2.0: Dream big: When ideas outran infrastructure

It was serendipitous that the author, was present as a visiting scientist in the summer of 1985 at Charles Cantor's laboratory (at the Department of Genetics and Development, Columbia University), when Cantor was invited for a meeting at Washington DC to the idea of Human Genome Project. It was amazing to see how Cantor and other scientists dreamt of sequencing 3.2 billion nucleotides of the human genome in 15 years. This was thought of at a time when the laboratories had limited capacity of sequencing of up to 200 nucleotides in a day.

The author had a first-hand experience of witnessing the excitement of scientists dreaming and imagining of the technologies that did not exist. Realizing the future potential of genomics for affordable healthcare, the author championed the cause by organizing the first workshop on Genome analysis in 1987 at MBU, where Cantor discussed genome sequencing technologies and provided a hands-on training on separation of chromosomes.

Under the Indo-USSR DST-ILTP programme, the author received funding for a project on "Repetitive DNA structure function and chromatin organization". This, in 1989 gave him an opportunity to witness Mirzabekov's laboratory's dreams of creating oligonucleotide chips for DNA sequencing. He had the good fortune to collaborate with them. In 1988, the Human Genome Organization (HUGO) was formed with Charles Cantor and Andrei Mirzabekov as two of the 42 founding council members from 17 countries [2]. To democratize genomics technology, HUGO expanded its membership to several countries and in 1991, the author was the first Indian, to be elected to HUGO membership.

The courage to begin a journey without a map

India then had access to genomics knowledge but did not have the requisite funds for sequencing. The Indian economy was constrained with a severe financial and foreign exchange crisis, and therefore all cost intensive projects such as genome sequencing were ruled out. However, under the visionary guidance of Dr. S. Ramachandran, then the Secretary, of Department of Biotechnology (DBT), and Dr. N. Seshagiri, then the Director General of the National Informatics Centre, in 1986-87 a computational biology program was initiated establishing a Bioinformatics Centre at the Department of Physics, IISc. This was a network of nine centers, prior to the creation of the NCBI at National Institute of Health in 1988. By late 1989, the scientific community began discussing about the risk and benefits of the yet-to-be-launched Human Genome Project (HGP). The author had a privileged access to the planning documents of HGP, from Cantor and these enabled him to foresee the benefits of genomics for India.

On 14th February 1990, Dr. Ramachandran held a meeting at DBT with Charles Cantor (then the Director of the Human Genome Center in California), and Indian molecular biologists including the author, to discuss India's role in the Human Genome Project. The author sent a note for the meeting to Dr. Ramachandran on Genome Analysis. A portion of that note is reproduced below as it became the basis for establishment of "Human Genome—Indian Initiative" under the aegis of the Department of Biotechnology (DBT).

"With the beginning of a national debate on human genome analysis it is necessary to visualise the importance and the limitations of taking up such an endeavor. In the following two pages an attempt has been made to highlight some of the aspects of the human genome project which can have great impact in the national context on biological research per se. While access to primary data is essential for knowledge-based analysis it is also worthwhile to participate and update experimental techniques so as to prepare for the forthcoming new information. This note contains only one's own perception of the problem and how in the Indian context this type of a project could be beneficial" (8th February 1990).

After discussion with Cantor about the 15 years roadmap of HGP, Ramachandran formed an advisory group that included the author to develop the "National Genome Analysis Programme" and sought the opinion of 32 institutions in India. Unfortunately, 90% of the institutions thought genome sequencing technology would be unlikely to have much biology and therefore this initiative did not fructify and India missed the bus to be a part of this mega scientific project that involved scientists from 20 countries (Science 2.0). China was the only developing country that was invited in 1999 to carry out 1% percent of the human genome sequencing.

Seeding genomics in India: Dawn of a new era

DBT initiated the genomics programme as projects in areas, that aligned with national needs. Two projects supported during 1991 were:

- Genome Analysis: Technology development and manpower training at MBU IISc, Bangalore to the author (Rs 2.9 million), and
- Genome analysis of genetic disorders common in India at AIIMS, New Delhi to Prof. I.C. Verma (Rs. 0.6 million).

The project at AIIMS focused on molecular genomic services for known genetic disorders and the author's laboratory explored an unchartered path of triplet repeats associated with neurogenetic disorders and the exploration of genetic markers of schizophrenia and bipolar disorder. This project was in collaboration with clinicians Drs. Sanjeev Jain and Gauri Devi of NIMHANS in Bangalore.

By the mid-90s, economic liberalization started improving the situation for Indian Science. By 1996 with Dr. Manju Sharma as the Secretary of DBT a national document, "Human Genome Indian—Initiative and Genomic Diversity and the People of India" was in place with a budgetary outlay of Rs. 200 million (then $6 million) for 3 years. This was miniscule sum compared to the US annual investment of $200

million for HGP.

During mid-1990's even a simple DNA test for beta thalassemia was not available in India, and samples had to be sent to David Wetherall's laboratory at Oxford for mutation analysis at a formidable cost. Therefore, a DNA diagnostics panel for five most prevalent mutations in India was developed through DNA sequencing at MBU, in collaboration with Dr Geeta Talukdar, RKM hospital, Calcutta. This diagnostic panel was commercialized by M/s Bangalore Genie in 1996 as the first commercialization of genomics knowledge in India.

IISc did not venture into establishing a major genomics center in late 90's, despite, a) MBU nucleating the genomics initiative, b) the presence of a bioinformatics center, and c) major computational capabilities at the Supercomputer Education and Research Center (SERC) at the institute. In 1995, during the formulation meeting of 9th Five Year Plan project at IISc, the author mooted a large project on genomics and molecular medicine. Unfortunately, it was voted out with near unanimity with the argument that "the genome sequencing was a technician's job not quite fit for the intellectual rigours of a top-notch academic institution."

Protecting the Indian genetic resources

Realizing that the large and diverse Indian genetic pool will be important in the post genome sequencing era, in mid 90's, several companies and institutions abroad were collecting samples of patients from Indian hospitals. The author tried to prevent such biopiracy [3] and during 1996 demanded genetic dividend for the contributing patients at various fora of the UN [4]. Consequently, the author was invited to contribute to "The Draft International Convention on the Human Genome" which was adopted by UNESCO in 1997**. India adopted this convention with necessary modification as "National Ethical Policy on

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**Article VI Intellectual property

1. The human genome in its natural state is not subject to private, national or transnational ownership by claim of right, patent or otherwise.
2. Intellectual property based upon human genome may be patented or otherwise recognized in accordance with national laws and international treaties.
3. The collection, distribution and use of human genomic materials and associated information shall be undertaken on a basis which reflects an interest of the original source and of the depositor of the material to an equitable share of the economic benefit of commercialization based upon:
   (a) use of the material and associated information;
   (b) the relative significance and/or unique nature and/or rarity of the genomic characteristic of the material and associated information; and
   (c) the original source and the depositor's relative contributions to the overall creation and commercial development of relevant intellectual property.

the Human Genome, Genetic Research and Services" in 2001 preventing biopiracy.

India in global genomics: When collaboration became a revolution

In 1996, a lecture by Dr A.P.J. Abdul Kalam described the development of India's rocket programme harnessed the collective strength of multiple institutions and industries. This was a visionary model of *Science and Technology 2.0* in action within India and truly inspired the author.

For the International Human Genome Project, India was a vast reservoir of nature's random mutations and a rich repository of biological knowledge. These offered several strategic advantages for understanding the human genome. With nearly a fifth of the world's population and with a tradition of large family sizes, India was an unparalleled resource for genetic analysis, particularly for dissecting complex disorders. The sheer size and diversity of the population also meant that a significant number of rare genetic disorders were likely to be encountered naturally. Furthermore, India possessed a strong foundation of medical expertise (with a large pool of skilled clinicians trained in modern medicine) and an extensive network of hospitals, clinics, and health centers. This infrastructure was exceptional and unmatched by many of the other developing nations. This premise and an ambition for a mega project on "Genomics and Molecular Medicine" took the author to Delhi in 1997 at CSIR-Center for Biochemical Technology (CBT) to establish India's first Functional Genomics project supported by DBT. This involved many clinicians, computational scientists, molecular biologists, geneticists and synthetic chemists dealing with peptide, and nucleic acids. The Indian genetic pool provided a unique opportunity to discover significance of human genome sequences of unknown function through mutation analysis. The idea caught the imagination of fresh PhD's Mitali Mukerji and Beena Pillai from IISc and Debasis Dash from Delhi University who did not have any prior experience of working in genomics. Curiously, it was these first followers, who made India a powerhouse in genomics.

The Functional Genomics Unit at CBT launched two initiatives in 1998 with a support of $2 million from the Department of Biotechnology. These were: a) to initiate genome analysis and understand its correlation with disease-based information available from the hospitals, and b) to develop novel computing and informatics techniques and tools that would help in the analysis of the genomes. DBT also supported projects like *Entamoeba histolytica* genome sequence at the Jawaharlal Nehru University, Delhi; genome diversity projects at the Centre for Cellular and Molecular Biology at Hyderabad, and the Indian Statistical Institute,

Calcutta. The Functional Genomics Unit at CBT created network of clinicians and a virtual network institution. This was a dream of Science 2.0, accomplished. A landmark achievement was deciphering the etiology of cerebellar ataxias, from molecular mechanism of triplet repeat expansion to the development of panels of genetic tests (NeuroPro Dr Lal's Pathlab). This was a two-decade long journey comprising three generations of scientists from Mitali Mukerji to Mohd. Faruq, and clinicians Satish Jain to Achal Srivastava from AIIMS Delhi [5].

Bridging silos and building trust

In April 1999 a pharmaceutical company M/s Pfizer India sponsored the development of human resources in pharmacogenomics and genome informatics at CBT to train clinicians. By 2000, India already had the competence to analyze and publish research papers on genome sequences. The first draft of the human genome sequence in 2001, enthused Pharma companies in India to contact CBT with their interest. The first knowledge Alliance "GENOMED" project with Nicholas Piramal India Ltd was thus initiated. The G.N. Ramachandran Knowledge Centre in genome informatics was established through a philanthropic funding from The Chatterjee Group (TCG). After the 9/11 event in the US, 14 BTech Graduates from the Indian Institute of Technology, Kanpur and several students from National Institute of Information Technology joined CBT with TCG fellowship to explore computational genomics. Their efforts led to the development and commercialization of bioinformatics tools PLHost and GenoCluster.

Several of these students moved on to complete their doctoral degree in computational genomics and system biology and are the present leaders in this field, both in India and overseas. By this time, Genotypic Private Limited was incubated at CBT and Strand Genomics (now Strand Life Sciences) was established at Bangalore. From 2001 to 2004, the Tata Consultancy Services joined hands with five CSIR Laboratories and 11 other Indian institutions to build BioSuite, a versatile portable software suite for bioinformatics under CSIR-NMITLI program. Another Science 2.0 initiative [6]. Rarely in Indian science, there has been such a close cooperation between knowledge generation and knowledge dissemination for commercial and social benefit. It established the advantage of being of early movers in any scientific field. In 2002, CBT was renamed as the Institute of Genomics and Integrative Biology. The second genomics institute the National Institute of Biomedical Genomics was established in 2009 at Kalyani in West Bengal.

Science 2.0 Genetic landscape of the people of India: A canvas for disease gene exploration

In the 10th Five Year Plan (2002-2007), CSIR created provision for a large funding for network projects in genomics like the Indian Genome Variation Project and *In Silico* Biology for Drug Discovery.

The International HapMap project was started in October 2002 to map global genomic variation in the human genome by drawing samples from diverse populations [2]. India had the option of joining this by contributing 30 samples or to initiate its own Indian Genome Variation (IGV) project. CSIR-IGIB chose the second option because the Indian genomic diversity could not be adequately represented in mere 30 samples. The international HapMap project decided to collect 270 samples from four populations (YRI African, CEU European, CHB Chinese and JPT Japanese), with a budget of $100 million. Concurrently and with a budget of $5 million, the CSIR-IGIB led Indian Genome Variation (IGV) Project analyzed 1,871 individuals, from 55 populations (32 large and 23 isolated). This was by strategically designing the experiments and involving five other CSIR laboratories (CCMB, CDRI, IICB, ITRC & IMT) and Partha Majumder from the Indian Statistical Institute [7]. The challenge was to coordinate with 24 Principal investigators, (unfamiliar to each other and without an experience of working in large consortia) assisted by a hundred students and technical assistants. Many technicians from The Center for Genomic Application (TCGA) also worked in this initiative. The TCGA** facility provided services to many smaller laboratories across the country who could not afford expensive equipment for genome sequencing and genotyping.

The key to the success of the IGV Project was the decision to entrust its project management and experimental coordination to two younger scientists at CSIR-IGIB Mitali Mukerji and Debasis Dash who led, respectively, the experimental and data management components. of this massive national effort. By 2008 a landmark paper with 150 authors, "Genetic landscape of the people of India: a canvas for disease gene exploration" was published. This heralded India's arrival as a noteworthy serious contributor to genomics [8]. Again, this was Science 2.0 realized.

This work provided the first comprehensive genetic map of the diverse Indian population and identified predictive markers for complex diseases and pharmacogenomic studies. Consequently, HUGO invited

** TCGA was first of its kind publicly owned privately managed core shared genomics facility, a collaboration (2004-9) between CSIR-IGIB and Institute of Molecular Medicine, a not for profit entity of The Chatterjee Group.

India to host the International Human Genome Meeting 2008 with the author, member of the HUGO Council, as its Chair. On author's invitation, Lalji Singh and Partha Majumdar joined this effort as Co-chairs.

The Indian Genome Variation Project was a collective effort and laid the foundation for coordinated projects in genomics in the country. In 2005 India was invited to join the PanAsia SNP project involving 10 Southeast Asian countries including HGP participants Japan and China [9]. These studies established that the genetic makeup of the population of India encompasses the diversity of the world and makes it an ideal setting for disease genetics, pharmaco-genomics and clinical trials. Genetically therefore India is seen as representative collective of global population as visualized by the great poet Rabindranath Tagore in his poem "Bharatatirtha" ("The Indian Pilgrimage") invites all of humanity to Indian shores, seeing the nation as a land of unity and vast humanity.

From lone warriers to synergistic research ecosystem

CSIR-IGIB kept pace with global genomics by 2009 when it sequenced the first Indian human genome. Subsequently by 2021 "IndiGenomes: a comprehensive resource of genetic variance from over 1000 Indian genomes" was completed [10]. Presently, with the support of DBT, the national effort, the "Genome India project" has completed 10,000 human genome sequencing from 83 populations in 2025 [11]. This study, leveraged insights from the Indian Genome Variation Project to identify populations that best represent the diversity landscape of India. The recently launched "Phenome India" project of 10,000 CSIR cohorts is a unique Science 2.0 initiative. It is gratifying to see how far we have come in genomics technology in India. In 35 years, a dream became a reality and empowered Indian healthcare providers with data on Indian population. This has indeed been a long and challenging but satisfying journey.

Economic impacts of genomics in India

The availability of indigenous technology, skilled workforce driven by advancement in clinical genomics has implied a growth of the Indian genomics market through its helping with cancer screening, testing of rare diseases and in personalized medicine. The Indian genomics market size was at $2.2 billion in 2024 [12] and its projected to reach $9 billion by 2033 at a CAGR (Compound Annual Growth Rate) of 16.1%.

Clinical genomics, oncology, prenatal testing and pharmaco-genomics are the key segments driving this growth. From two startups in the year 2000 focusing on genomics, the number has crossed 1000 in 2025. Now

over 400 clinical laboratories in India have adopted genomics in clinical practice [12]. Almost 10,000 people are employed in genomics-related work with 40% in wet labs and 60% in bioinformatics. The vision of 1998: "*In this scenario it is imperative that Indian scientists, medical practitioners and pharmaceutical industries should come together to develop the necessary expertise and utilize our rich genetic wealth to convert it into economic wealth*" has been realized.

Science 3.0: Open-source drug discovery: Linux for pharma

The CSIR network project "*In Silico* Biology for Drug Discovery" identified and patented several novel non-active site drug targets for *M. tuberculosis* but none of the large pharma companies were interested in exploiting that knowledge, given that the market size for tuberculosis was only $300 million. Although the *M. tuberculosis* genome sequence was made available by Pasteur Institute in 1998, 60-year-old treatment continued and 4000 TB patients died everyday across the world. Nearly, 25% of the deaths occurred in India. It was therefore realized that a system biology level approach is needed to develop non-toxic drug targets, that are affordable. Strong intellectual property increases availability but compromises affordability. Inexpensive discovery needs open innovation and shared wisdom. Inspired by the open-source model in information technology, like the Linux, the Open-Source Drug Discovery (OSDD) project for Tuberculosis was conceptualized in 2007 and launched in 2008 as a Team India project with global participation led by CSIR [13]. The project was met with a significant skepticism nationally, however eminent scientists like William Hesseltine, Bernard Munos appreciated and encouraged the author to take it forward. The concept was to collaboratively excavate and aggregate the available biological and genetic information of *M. tuberculosis* that lies buried in literature to hasten the drug discovery process using the system biology platform. By 2010 *M. tuberculosis* genome was annotated as a virtual community effort through crowdsourcing of 800+ students and researchers. This Connect to Decode initiative mined 45,000+ publications and achieved a 99.5% annotation of all the genes. This was Science 3.0 in action and it was accomplished at a time when working in virtual space was not even heard of [14]. By 2013, the OSDD had provided an unconventional global scale virtual collaborative platform for discovery of new drugs for tuberculosis using computational to experimental chemistry. OSDD became a distributed virtual laboratory with over 8700 participants from 130 countries and became the largest crowd-sourced scientific project in the world, attracting global attention, with extensive coverage in the literature [15, 16]. Hence not discussed further in this article.

By 2015, the OSDD programme was subsumed into the Indian TB Research and Development Consortium (ITRDC) project led by Indian Council of Medical Research, which created novel method of asset utilization and capacity building at a negligible cost, leading to positive economic impact [17]. The OSDD programme is now an integral to the development of the national intellectual property rights (NIPR) Policy 2016 and it has been accepted as a model for neglected disease drug discovery by WHO.

OSDD has now gone global. The power of open source was amply demonstrated during the Covid-19 pandemic and many open-source projects were initiated. In 2019, the Tata Trust established the Open-Source Pharma Foundation in Bangalore to take OSDD initiative forward. Today, a major Science 3.0 initiative is the crowdsourcing of mapping the human brain. Surprisingly, the Indian scientific community, despite a large student community has not initiated crowdsourcing projects. On introspection it seems, we as a community need to develop chutzpah to do things differently, despite the skepticism every novel initiative encounters.

Science 4.0: AI enabled: Affordable and quality healthcare

The World Chess Championship 2024 has shown the acumen of the young Indian mind. Boys and girls now are world champions at the age of 18 when their inspirational leader Viswanathan Anand had similar accomplishments only at age 30. Power of crowdsourcing of young mind is amply demonstrated in the previous section. Despite phenomenal technological development in life sciences in India, the average life expectancy increasing from 32 to 72 since independence, affordable quality healthcare for all still remains a distant, elusive dream. Availability of large number of human genome sequences along with clinical information and other multi-omics datasets hold the key to curative and preventive affordable quality healthcare of the future. However, this needs properly orchestrated, genuinely synergistic effort by professional scientists and medical practitioners alongwith AI startups and thousands of high school and undergraduate (MBBS, BTech, Biotech etc.) students with expertise in using AI tools can contribute effectively.

Science 4.0 will have all the elements of Science 3.0, including crowd sourcing the talent plus the new AI tools like Chat GPT 5.0, Google Gemini, Alpha Fold 2.0, and IBM Watson as research assistants. Indian scientific leaders need to utilize talented young minds in such data-driven, citizen science. Learning by doing, will be the new norm of the future education and in this, gifted GenZ Indians would need to lead.

The catalytic and leadership role of INSA

The Indian National Science Academy should spearhead this movement in the country by formulating policy and creating opportunities for capacity building and participation of the young generation. It should establish a working group of fellows with complementary expertise to create a vision map and implementation strategies. In the biology/pharmaceutical realm this will allow creation of a road map for the development of AI agents to identify novel biomarkers specific to the Indian population for wellness; identification of biomarkers of early onset of non-communicable diseases in the Indian population; AI tools for repurposing FDA approved drugs for different diseases based on biochemical pathway analysis and through a system biology approach. Equally important is the development of predictive AI tools for identifying adverse drug reactions and drug–drug interactions, enabling personalized preventive healthcare through recommendations on diet, lifestyle, and wellness interventions. Integrating traditional knowledge–based systems such as Ayurveda with modern biomedicine can pave the way for the holistic medicine of tomorrow. The vision should be to build *Developed-in-India Healthcare AI Agents* that are trained on data of Indian population, reflective of its diversity. This will not only serve Indians but also the broader reals of developing world with affordable, high-quality, and contextually relevant healthcare solutions. This will be science diplomacy for global good, at its best.

Way forward: Science and technology for nation building through career building

By the time this article reaches the Indian scientific community, the newest AI Scientist, *Kosmos*, will likely have arrived. This new generation of AI systems will not only read and comprehend vast volumes of literature but also make novel discoveries. In such a landscape, imagination and wisdom will become more valuable than mere knowledge. These will be the true fuel for disruptive innovations.

How should the Indian scientific community prepare itself to contribute to science and technology aligned with national goals? In 2024, India emerged as the third-highest contributor to scientific publications worldwide (as per the Web of Science Index) and also ranked third in the top 10% of highly cited articles spanning applied, physical, and life sciences. The challenge before us now is to translate this high-impact research into innovations that yield tangible economic and societal returns. To achieve this, the Science and Technology Departments of the Government of India, along with the Academies of Sciences and Engineering, must together create a blueprint for the science and technology of the future.

One that leverages India's natural resources and traditional knowledge base, offering a strategic advantage over other nations.

This vision must be driven by young, talented scientists and not left to only seniors, as they will be the future leaders of Indian science and technology and should take up ownership of emerging this landscape. It is important to remember that vision is not transferable, dreams belong to individuals, and a leader is, above all, a seller of dreams. Future discoveries and disruptive innovations will arise at the interfaces of disciplines, demanding new organizational structures and a newer model of leadership and dynamism.

The ongoing shift from the industrial age to the knowledge age, accelerated by the information technology and AI revolutions, calls for organizations that have:

- Flexibility to take on emerging challenges,
- The ability to harness multidisciplinary expertise,
- Mechanisms to reduce the time from concept to implementation, and
- Agility in building new skills through networking and crowdsourcing talent.

Only such organizations will survive to be the major players in the globally competitive frontiers of science and technology.

A successful model already exists in the Academy of Scientific and Innovative Research (AcSIR), the world's first virtual university established to create transdisciplinary human resources without additional capital investment. Similarly, India needs to create virtual laboratories and networked organizations to explore new frontiers and establish leadership in niche areas such as biomimetic materials, advanced manufacturing technologies, industrial synthetic biology and green chemistry, institute of sustainable engineering, etc. These can be achieved by drawing expertise from national laboratories, university departments, industrial R&D units, and startups to undertake challenge-driven projects.

Young faculty must be mentored and empowered to tackle bold, high-impact problems and evolve into future leaders of Indian science and technology. Tomorrow's leaders must be deep domain experts with a broad cross/interdisciplinary understanding, capable of integrating insights across fields and envisioning the future. We must nurture scientists who are problem-solvers with a passion for discovery and not content with incremental science or copycat technologies.

Funding agencies should encourage high-risk, innovative ideas at the cutting edge of science and technology, and reward ambition over

guaranteed success. To make this possible, our scientific audit system should be restructured and success metrics must be defined at the time of project sanctioning. Experience shows that industry funding readily follows innovative and purpose-driven ideas.

Our reward and award systems also need rethinking. We must move beyond recognizing only individual excellence to acknowledging the collective achievement of teams and the impact of their work. This would allow multidisciplinary collaborations to be duly recognized, enabling multiple scientists to share honors such as Academy Fellowships or National Awards. Such a shift will remove the current disincentives for collaborative research.

If India is to become a developed nation by 2047, we must apply high-level science and technology to ground-level problems. Let us conclude with the timeless, sage words of Mahatma Gandhi, spoken at IISc on 12 July 1927:

"Just as some of the experiments in your laboratories go on for all the 24 hours, let the big corner in your heart remain perpetually warm for the benefit of the poor millions."

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7

Legacies and Ensuing Challenges of Indian Science Academies in Changing Global Contexts

T. Ramasami

Scope

Indian National Science Academy (INSA) is celebrating its 90 years of service to the Indian science community in the year 2025. It is a long journey. INSA has witnessed several important changes in the external environment in the country since its inception in 1935. The National Academy of Sciences of India (NASI) and Indian Academy of Sciences (IAS) founded in 1930 and 1934, respectively were functional when the precursor of INSA was established. Stated objectives of NASI in 1930 was to provide a forum for Indian scientists to publish their research work and create a platform for exchange of ideas. It may have carried the cultural gene of democratization of Indian science. IAS prioritized the progress and working for the cause of science as its own purpose. INSA carried the objective of promoting science in India and harnessing scientific knowledge for the cause of humanity and national welfare from its inception. All the three science academies have evolved since their respective start. Their evolutional histories also may carry the perspectives of their respective founder Presidents and the social contexts in which they were founded. The then British Government was not enthusiastic to support research and innovations. The formation of science academies in India was primarily the initiative of scientists as global citizens. Many years later, there were suggestions that all the three academies could be merged and converted into a single legal entity. Legacies of the three academies differ, and they seem to elicit complementing more than competing stances. It is my personal view that the possibility to grow all the three academies to serve different aspects of science, research, and innovation sector in the social context of India@2025 could be explored. Indian science landscape has changed during the last three decades. Science might have to play more defining roles in shaping the future of India. The

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three academies could play differentiated but collective roles in shaping the future of India as an important power in the ensuing global knowledge economy. Indian science sector could enrol itself into the national aspiration to emerge as a leader and participate in the nation building process.

Role of INSA in the Indian Science Landscape: A suggestion

Science as a scholarship activity could retain the individual pursuit mode of work for advancement of knowledge for its own sake. Technology as a market driven activity demands close connections with users of knowledge and team effort. Global leadership of nations in global knowledge economies can rarely emerge vertically from individual pursuits. It calls for collective and gathered national efforts and interplay of several stakeholders connecting knowledge to economy. If IAS, NASI, and INSA could divide their roles and functions to match the differentiated knowledge needs of mind to market space namely discovery, translation and innovative deployment of scientific knowledge, India's expectations from the science community could be better met. INSA could focus more on the impact of science on national economy and welfare. It is an observation from the legacy of INSA that the academy is better positioned compared to the other two to focus on nationally impactful knowledge on the economic and social welfare agenda of the country.

Evolutionary history of Indian National Science Academy

INSA has evolved into the science academy which works closely with the Government of India on the national scene and serves as the two-way window of Indian science to the global community of researchers. India became politically independent in 1947 when all the three academies were in their second decennium. The INSA president Shanti Swarup Bhatnagar in 1947 was also then the Director General of Council of Scientific and Industrial Research. Executive leadership of Indian science and the presidency of Indian National Science Academy was held by the same person in 1947. The legacy of INSA reveals a strong connection between the Academy and the Government of India with more than 40% of the past presidents having held executive leadership positions in the Government sometimes even concurrently. Connecting knowledge to the national welfare was the stated agenda of INSA even in the early stages. Participating in the national tasks where science is an input is in the evolutionary history of INSA.

When the Indian science sector was perceived to suffer from talent supply chain problems for study of science and career with research, the Government of India launched in 2008 a scheme named "Innovation in

Science Pursuit for Inspired Research". INSA has even embraced the role of implementing the scheme and started to play a direct and implementing rather than advisory role. Today there is a separate section in INSA for the management of INSPIRE. Totally 1601 people have availed the fellowship and more than 926 have been mainstreamed into the Indian Science sector [1]. Performance reviews of the INSPIRE faculty Fellows reveal a favourable outcome to which INSA could take credit. Globally the science academies are engaged in the promotion of science and limit their functions to one of non-participating advisors. INSA has played differentiated roles from other science academies. Indian science is now better poised for contributions to national welfare than ever before. It could take direct and active part in connecting the stakeholders and shareholders of scientific knowledge and not limit its role only to the promotion of scientific research in India.

Changing Indian science, research, and innovation landscape since 2000

Indian science, research, and innovation landscape has been changing during the last three decades. There has been a planned expansion of the Science and Research base of India. The Number of full time equivalents of research and development professionals has increased from mere 134000 in 2003 to 334000 in 2020 [2]. The relative position of Indian science, research and innovation sector in global ranking has improved in the last 25 years as shown in Figures 1 and 2 as evident from the number of scientific publications in Web of Science and Scopus databases, respectively. There has been a quantitative improvement.

India is no longer a fringe player in the global science, technology, and innovation space.

With respect to number of publications in scholarly journals, India's rank has improved by about 10-12 places during the last 25 years. India is one of the top five nations with respect of number of publications. In terms of highly cited paper in Essential Science Indicators on Web of Science database also, India is one of the top five knowledge powers.

Australian Strategic Policy Institute in 2024 has ranked India as one of the top three knowledge powers based on the study of strength in sixty-seven critical technology areas [3]. To quote from their own findings, "India is also emerging as a key centre of global research innovation and excellence, establishing its position as an S&T power" [3].

There is evidence that Indian science, research, and innovation landscape is improving and gaining global attention. In Global Innovation index India was ranked sixty-nine in 2013. In 2019 ranking has improved

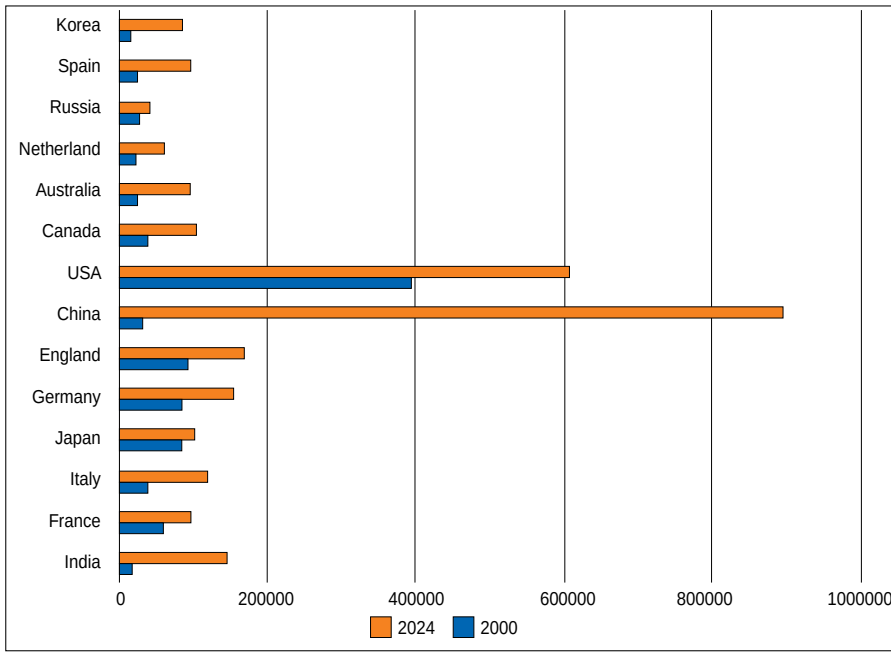

Figure 1: *Relative performance of nations in publications since 2000 (Source: Web of Science database)*

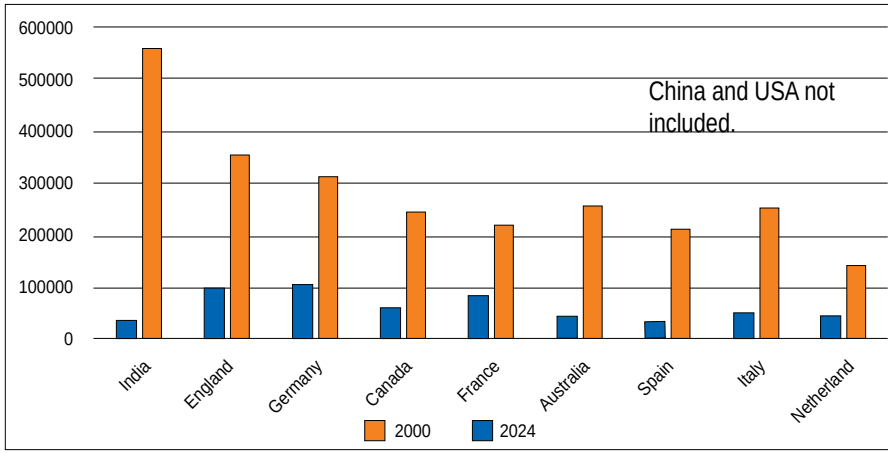

Figure 2: *Relative performance of nations in publications relative to 2000 (Source: Scopus database)*

to thirty-nine. (Source: Global Innovation Index Database, WIPO, 2024) [4]. There is adequate evidence in support of the Indian science, research and innovation landscape gaining global attention based on relative improvements during the last twenty years. India might be the highest ranked innovation country among all the lower middle-income group of nations [4]. However, there is a prevailing gap in connecting relative strengths in science sector to applications of knowledge and

innovation led manufacturing in the self-interests of the country. Scientific research in non-strategic sectors has remained an individual pursuit-based activity.

Connecting knowledge to societal benefits: A work in progress in India

India's position in scientific publications and innovating potentials might have improved since 2000, but India's share of high technology trade is abysmally low. The share of India in high technology trade estimated globally at US$ 3.7 Trillion in 2022, is about 1.1% [5]. In knowledge economy, countries with higher competitiveness in high technology trade is expected to benefit more significantly. While there have been discussions on the level of funding required for bolstering science, research, and innovation sector in India, it is not evident as to what percentage of Gross Domestic Product of India is related to outputs from research and development. A quantitative assessment of scientific research led economic growth benefits to the country might be still coming. Connecting knowledge to societal benefits in India is at best considered work in progress. It is appropriate to consider the layers of changes knowledge undergoes by networking with other players before its benefits become tangible and gainful.

Mapping of layers of transformation knowledge undergoes in connecting to society

An attempt has been made to capture the layers of transformation new knowledge from laboratory research undergoes before it brings societal benefit in the form of either wealth or value generated. In an emerging economy like India, there are several and critical gaps which limit the conversion of knowledge into wealth or societal value. While research leading to a publication could be an inspired activity of an individual or a cohesive group, conversion of a scientific output in the form of national good calls for interplay of several other players including users and the Government. Steps involved in knowledge >> know-how- >> Show-how >> Do how >> Use how transition are captured and presented in Figure 3.

Creative knowledge from academic pursuit after reduction of risk of failures in applications becomes a know-how in the hands of a researcher. Know-how in the form of an innovation passes through show-how in the hands of an innovation driven industry before it becomes a technology with commercial value and reaches Technology Readiness Levels attractive enough for industries to invest resources upon. Most public funded research in India does not go beyond Technology Readiness Levels of 3.

Special efforts are needed to grow scientific research outputs to Technology Readiness Levels of 5 or 6.

Figure 3: Multiple layers of transition of knowledge into socially gainful product

A perceived weakness Indian Public Funded Research and Innovation System in translating knowledge into societal value

One of the major shortfalls in the Indian science, research and innovation landscape is the level of participation of private sector into research [6]. The conversion of know-hows into show-how demands the formation of innovator network built on the foundation of mutual trust among researchers into users of technologies or innovations. There have been successful examples of research in private sector having reached the marketplace in the drug and pharmaceutical industry. Significant levels of research and its outputs emanate from public funded activity. Reaping benefits from public funded research for national benefits could call for changes in mind sets from technology transfer to technology relationships models.

Next level of changes required in the indian science, research, and innovation landscape

Next level changes that could help cause of conversion of knowledge into societal value could be considered. A tentative list is provided here.

1. Further strengthening of the Indian science, research and innovation system, breaking the silo mindset of the research and enterprise communities.

2. Positioning a platform for Public-Private-Partnership for Research and Innovations with a sizeable and non-lapsable fund.
3. Selecting top ten research and innovation areas with global leadership potential backed by past performance registered during the last ten years for delivering superordinate goals within 5 to 10 years.
4. Positioning a framework for Research and Innovation Alliances among academic, research and industrial partners with high technology trade objectives.
5. Tasking ANRF to deliver superordinate goals based on R&I and funded under PPP over a period of 5 to 10 years with sound monitoring and periodic review mechanisms.
6. Outputs and outcome-directed investment strategy with critical level funding for delivering superior goals.
7. Establishing a special fund (matching about 15-16% of national investments) for supporting open-ended basic research under investigator centric competitive grants.
8. Establishing globally benchmarked self-sustainable national centres with committed support for five years in five selected critical technology areas (like, for example AI, machine learning, communication, space, renewable energy, low-carbon energy fuels) with cross-cutting impact on the Indian industrial sector.
9. Inviting research proposals for responsible innovations in the areas of climate change, b) low-carbon footprint technology alternatives, c) affordable human health care.

Roles of Science Academies in ushering next level changes in the Indian science, research, and innovation landscape

A *Preparation of insightful research backed knowledge documents*

1. For leveraging comparative national strength in the developmental agenda of the country.
2. For connecting research and innovations in specific areas for India gaining competitive advantage in High Technology Trade.
3. For strategizing institutional and human capacity building for leveraging comparative strength and competitive advantages in the innovation sector.

B *Championing for building human capacity for meeting future needs among*

1. Academic and research sectors for aligning human capacity building in research and innovation in solution science and training of solution designers.

2. The stakeholder community (Private and Public Industry) for forming alliances with the academic and research community for work on solution science and development of solution designers.
3. The stakeholder community for creating employment opportunities for trained researchers and initiating in-house research capacity in Private sector units.

C *Championing technology designs for low carbon footprint development*

1. Among research and development institutions and researchers on research for circular economy and low carbon footprint technology initiatives.
2. Preparation of technology documents on greening of critical industrial sectors and listing of stimulant and regulatory imperatives for ushering responsible innovative practices in manufacturing.
3. Among private and industrial sectors for financing research and innovations for green technologies and solution design.

D *Advocacy for responsible innovations for superordinate goals and targets*

1. Championing strategic alliances and designer partnerships among knowledge institutions with proven past performance.
2. Effort to interconnect competencies and resources for the formation of alliances for delivering on a) national commitment to GHG emission control, b) gaining global leadership in critical technology areas, and c) establishing virtual national centres in areas of comparative strength for India.
3. Among private players and national funding agencies for resource allocation for delivering superordinate goals and targets.

E *Proactive peer preview assistance to the national research funding agencies*

1. Science academies through their network could provide proactive peer preview support in establishing a) national virtual research and innovation centres in areas of critical needs, b) research and innovation parks under PPP model, and c) building human capacities in areas of future needs.
2. Identify areas most suited for PPP model of research and mounting binational technology missions for gaining competitive advantages in global markets.

3. Extend peer evaluation and monitoring support for programs with superordinate goals and targets as an internal alert for funding agencies.

Role of Indian National Science Academy in shaping science, research and innovation landscape needed for *Viksit Bharat*: A suggestion for consideration

INSA carries a legacy goal of connecting knowledge for national welfare. Several presidents of INSA held positions in the government of India and tried to create an organic connection between knowledge sector and the national needs. The current Government has already presented a national goal in Viksit Bharat. The required 4.3 times per-capita increase in Gross Domestic Product from current levels cannot be realised without connecting knowledge sector to nation-building goals. Whereas most academies may have championed for higher R&D investment and "what is good for the science sector," INSA could speak for "what is Indian science good for" in delivering on the Viksit Bharat goals.

While Indian Academy of Sciences could foster individual centric scientific research as its main agenda of focus, INSA, as a neutral and apex body with stronger historical connects to the Government of India as well as science academies elsewhere in the world, could speak for formation of networks and alliances which focus on nationally impactful research outcomes. Individual pursuits in research tend to focus on peer recognition globally. Superordinate research goals with potentials of national impact call for system approach. India has done well in strategic research sector in space, atomic energy, and defence since they adopted methodologies of collective and team efforts involving large number of scientists and adopting system approaches. In non-strategic sector, green revolution is a successful case in India where the science sector worked as a system. Peer recognition in India for long has been focused on individual pursuits of science. Celebration of Indian science by citizens seems the next best action of the research sector. May be INSA could now examine recognitions based on national effects and impacts rather than individual excellence in efforts. The recent election of fellows to the Academy tends to indicate a move in such directions. It has been ventured to make generic suggestions to all the science academies in India. May the wise counsel of INSA study the suggestion and retrofit what suits the academy best in delivering on its own stated goal of harnessing scientific knowledge for the cause of humanity and national welfare.

Epilogue

In the life of an institution like science academies, 90 years might not seem long. INSA has completed 90 years in 2025. What the academy does in the next 10 years could be defining not only in its history but also in that of the nation. Nation building roles of the science sector need to be conveyed and, if necessary, reiterated several times. INSA could play the torchbearer and take a direct part in delivering its legacy goal of "harnessing scientific knowledge for the cause of humanity and national welfare." Gandhi declared "science without humanity" one of the seven social sins. Could INSA become the national champion for Science for Humanity"!

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T. RAMASAMI is a respected leather scientist and researcher who was Director of CSIR-Central Leather Research Institute, Chennai, for over 10 years. He also held the position of Secretary to the Government of India and was instrumental in formulating the Science, Technology, and Innovation Policy of 2013 and launched several new R&D funding programs, such as INSPIRE and PURSE. He is a Fellow of several prestigious academies, including the Indian National Science Academy, the Indian Academy of Sciences, and the World Academy of Sciences. He is bestowed with several prestigious awards and honours like Shanti Swarup Bhatnagar Prize, Padma Bhushan and Padma Shri by the Government of India.

8

Science Academies and their Role in Nation Building

P.S. Goel

Scope

India has three science academies, The Indian National Science Academy (INSA), Indian Academy of Sciences (IASc) and National Academy of Sciences India (NASI). The three science academies were established by great scientists at different times in Delhi, Bangalore and Prayagraj, respectively. In addition, India has one engineering academy, the Indian National Academy of Engineering (INAE). INSA has been authorized to be the nodal academy for international cooperation with science academies of other countries. Government of India also entrusts INSA for scientific interaction with other countries. Scientifically, all three have a similar mandate for fostering the cause of science in the country, and each has a separate section for engineering, though there is a separate engineering academy, the INAE, based in Delhi.

INSA is celebrating 90 years of its service to the nation. INSA and the other two science academies have played a big role in the cause of science in the country by honouring scientists for their achievements. Becoming a fellow of any of these academies is a big honour, and there is always a desire among scientists to become a fellow of these. The academies are rigorous in their selection process. In addition, these academies organize various scientific events on topics of current developments in science. Much of these depend on individual fellow initiative and also the initiatives of the governing body.

On this occasion of 90 years of INSA, there is perhaps a need to examine the role of scientific academies in nation building and expand their role beyond recognizing the scientists for their exemplary work, and encouraging others to achieve the distinction.

Background

During mid-1980s, the Government of India (GoI) set up a Scientific Advisory Committee to the Cabinet (SAC-C) with Principal Scientific

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Adviser (PSA) as its chairman, to advise the cabinet on issues related to Science and Technology. The presidents of the three scientific academies, the president of INAE, the secretaries of all the scientific departments, member-science of the planning commission, and a few experts were its members. For about a decade, SAC-C met regularly, deliberated on various Science and Technology issues, and conveyed its recommendations to the Government. Ironically, while the academies participated through their representatives, these representatives rarely took up specific problems of society, nor did they make an effort to consolidate the views of the academy and present them. Most participation was at a personal level.

The SAC-C existed till 2014, and thereafter it was not reconstituted by the present Government. It was so perhaps because there was no one to explain the important role of SAC-C to the new government. The new PSA appointed by the new government had not been part of SAC-C earlier, and though PSA's office became a focal point for coordination among the scientific departments and connecting them to the Prime Minister's Office (PMO), it did not carry out the function for which the SAC-C was created. The science academies continued their routine work and coordinated with the Department of Science and Technology (DST), which is their funding agency. Largely, the academies worked with disconnect from the policy makers of the government, and also from the public at large in respect of communicating contemporary scientific developments to the public or the government.

Science and engineering academies role in nation building

In 2008, INAE had chosen a new path of conducting specific studies of concern to the society and needing engineering interventions. Some of these studies were supported by Dr R. Chidambaram, then PSA like the study of changes in the mining industry during the last 50 years; recycling scrapped vehicle waste; technologies for rural areas and the like. INAE also conducts a flagship program, "Engineer's Conclave" every year on two themes important to the country and comes up with implementable recommendations. Although some of these recommendations have been relevant, such as the road map for a Smart City, or adaptation of Engineering Interventions in Sundarbans to develop it on lines of Netherlands, it is intriguing that invariably these have remained in office files.

Based on the experience of SAC-C, we envisage three roles for science academies:

1. Connect the government with emerging S&T issues needing government interventions, be it a new field like Quantum Technologies, encompassing education, technology development like inertial

sensors or Quantum computing. If the scientific community finds an emerging scientific field that may help in energy, a new development in nuclear fusion, a new disease coming in Africa and we need to start developing a vaccine much before it lands in India, etc. Such issues should be brought to the notice of the government through PSA or the concerned scientific department.

2. Connect government to the scientific community. Government has its priorities and the concerned department is informed, but the scientific community across the country remains unaware of key policy developments. For esample, the government might have allocated funds for developing certain capability such as new generation of batteries with 1000 WH/Kg capacity. The academies can create a seamless mechanism to transfer such information to the researchers in respective fields.
3. Connect people to science through continued dialogue. For example, there is lot of fear amongst the masses from nuclear power and this can be remedied by explaining them the safety is built in the reactors. We know that that the nuclear power reactors built in India are safer than walking on the road, but we have failed to communicate this to the public. There are several such societally relevant issues that are related to awareness of current or emerging science and technologies, the academies can proactively play a meaningful a role.

Possible mechanism for Science Academies and INAE to be more effective in nation building

Now that we do not have SAC-C or its equivalent mechanism and there is an interest in academies to play a constructive role in national building, it is suggested that a new body, such as the National Scientific Coordination Committee (NSCC) be created and be serviced by the DST, GoI. Its suggested configuration and mandate are outlined below.

National scientific coordination committee

1. NSCC shall have a member each from the three science academies, INAE, Indian Council for Agricultural Research and Indian Council for Medical and Social Science Research. These members will be mandated to present the view of the academy and not their personal views. This will call for due diligence at the the academies level;
2. NSCC shall also have the seven scientific secretaries, or their senior representatives, with sufficient experience with matters of science;
3. NSCC will be chaired by rotation, by the presidents in INSA, IASc, NASI, and INAE for a term of 2 years;

4. NSCC may request PSA or its scientific representative to be a member;
5. Secretary DST may appoint a senior scientist as secretary to NSCC, who will coordinate the meetings, follow-up actions etc.;
6. Chairperson NSCC may co-opt expert(s) for any meeting, relevant to the agenda of the meeting;
7. Any member may propose agenda points to the president that he/she thinks are important for the country;
8. Recommendations of the NSCC may be submitted to the government through the secretary DST, PSA, the secretary of the concerned scientific department, or any other channel. The recommendations should be implementable actions, identifying the agency to implement;
9. NSSC may set up committees, task forces, and study teams as needed;
10. NSCC may meet once in two months through VC and at least two meetings must be in person;
11. NSCC may prepare an annual report by the end of December every year, summarizing the deliberations of the corresponding year. These could be in open access except the aspect of national security.

Concluding remarks

INSA should consider charting a new trajectory, not only for itself but also for other S&T professional bodies, to proactively play a meaningful role in nation-building. The world is moving rapidly with new technology waves like the Artificial Intelligence, Quantum Technologies, Synthetic Biology, Robotics and High Power LASERS in Scientific and strategic domain. All of these have immediate and long-term implications for society, related issues of ethics, cyber and space laws and legalities thereof and the academies need to proactively prepare India for the future and do so in real time.

This would require a new mechanism and new synergies for all the S&T academies to work in unison under one platform and for a singular objective of national well-being and safety. They would need to identify the issues, and create a white paper on the issues involved and the way forward with concrete action items. It's important to realize that the 21st century will be increasingly evolutionary than the last one, hence a faster turnaround time, and a more proactive approach towards understanding the application and implications of emerging technological waves and

related sciences is required. Vikram Sarabhai famously said that to gain respect, one needs to assume responsibility. It is time for academia to assume its sanguine responsibility and deliver on its societal promise.

P.S. GOEL was Secretary, Department of Ocean Development (DoD) and was responsible for transforming DoD into Ministry of Earth Sciences (MoES). He was the first Chairman of Earth Commission. He oversaw commissioning of Tsunami Warning System of India, initiated the modernization of IMD and pursued exploration of deep oceans. Currently, Dr Goel is Honorary Visiting Professor at National Institute of Advanced Studies. He is chairing Technology Research Board (TRB) of Ministry of Earth science.

Dr. Goel contributed significantly to the mission planning for remote sensing, communication and scientific missions and authored over hundred research papers in referred journals and conferences. Dr Goel was Chairman of spacecraft systems for IRS-1, Project engineer AOCS for APPLE and Associate Project Director, INSAT-II. He was Director ISRO Satellite Centre from 1997 to 2005 and a member Space Commission. He was President of Indian National Academy of Engineering (INAE) and Vice President, Aeronautical Society of India, Dr Vikram Sarabhai Distinguished Professor of ISRO. Dr Goel was awarded the Padma Shree in 2001. He received several other awards including Distinguished Scientist Award of ISRO and life time achievement award of INAE. He is fellow of Indian Academy of Sciences, Bangalore; National Academy of Sciences, Allahabad; Indian National Science Academy (INSA), New Delhi; Institution of Electronic & Telecommunication Engineers, New Delhi; Aeronautical Society of India, Bangalore; and Third World Academy of Sciences. He is also a Member, International Academy of Astronautics, Paris.

From Missed Opportunities to the Rightful Place

V.S. Ramamurthy and D.K. Srivastava

"A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill."

— Science: The Endless Frontier – Vannevar Bush

Scope

It is widely recognised that the rapid scientific, technological and economic advancements of the USA, and, more recently, of China, are the result of their massive investments in higher education, research and entrepreneurship. India's considerably slower growth post-independence can be directly attributed to subcritical efforts in these very sectors. We argue that it is still not too late for India to catch up and gain its rightful place amongst the comity of developed nations by providing the right fillip to higher education, research and entrepreneurship.

Introduction

The twentieth century was an important turning point in the history of science and technology. Not only did the number of fundamental scientific discoveries made during the century far exceed the number of discoveries made in similar periods anytime in the past, but the century also saw irreversible changes in the way in which scientific research is carried out, technologies are developed and taken to their desired end use and economic development.

An important development during the century, following the well-known Manhattan Project, was the bootstrap set in by the new scientific discoveries—new scientific discoveries leading to new technologies, new

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technologies leading to new instruments with far superior capabilities and the new instruments leading to more new scientific discoveries. While this quickly pushed the limits of knowledge beyond the known horizons, this also made research more dependent on sophisticated instruments and, therefore, more expensive. To remain competitive, scientists increasingly became more dependent on funding agencies for resources.

Yet another important development of the century is the emergence of high-technology products and services in the marketplace. While some of these came out of the well-known Manhattan Project itself, the decades witnessed an increasing role for non-government business entities to invest in research to dominate the marketplace both in terms of new products and services and in terms of market competitiveness. Scientific and technological knowledge emerged more and more as a commodity to be acquired, protected and traded. Rigid enforcement of intellectual property rights for commercial reasons led to restrictions on cooperation among scientific groups and duplication of efforts. It is not surprising that research at the frontiers also emerged as resource intensive.

The United States of America—the Trend Setter

The United States of America was the first country to recognise the changed scenario and make full use of it for advancing its national interests. In 1945, soon after the cessation of World War II hostilities, Vannevar Bush, head of the US Office of Scientific Research and Development through which almost all wartime military research was coordinated, submitted a report, "Science, the Endless Frontier", to the President of the United States [1]. The report led for the first time to a national policy for Science and Technology and a national budget for research. It also led to the creation of two agencies, the National Science Foundation (NSF) and the Defence Advanced Research Projects Agency (DARPA), to coordinate research priorities and funding. Many business houses like IBM, AT&T and others also started investing in Research and Development as a part of their business strategy. An ecosystem for innovation and entrepreneurship to convert knowledge into wealth also evolved. Silicon Valley in California and Boston's Technology Corridor (Route 128) are two of the early success stories of this new ecosystem. It is not surprising that the USA leads the world not only scientifically but also technologically and economically. The USA was also the first country to recognise that it can't live in isolation. Recognising the critical role of trained human resources in any national strategy involving Science and Technology and their own limitations, the US flooded their educational and R&D institutions with students and researchers from across the globe.

Many countries across the world emulated the US model in their own way with varying successes, but the USA still dominates the frontier science scene and the high technology marketplace globally (Fig. 1). The hierarchy of the economies over the post-WWII decades of the century has remained essentially the same. The US has retained its number one position in GDP over the entire century. It is not surprising that the twentieth century is often referred to as the century of the United States of America.

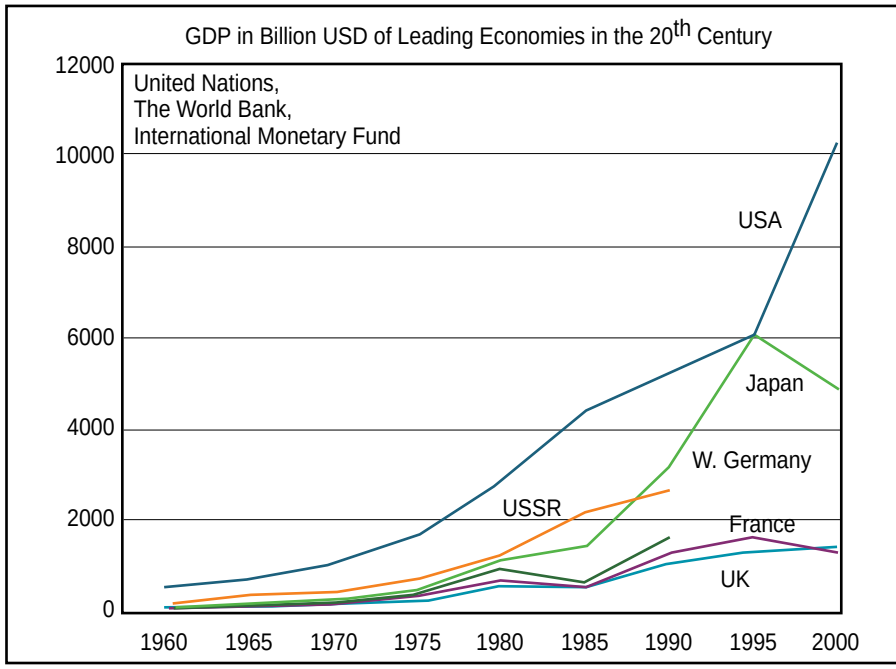

Figure 1: *Growth of GDP of leading economies during the post-WWII decades*

The People's Republic of China—The dark horse of the twenty-first century

The People's Republic of China (PRC) was founded on October 1, 1949. In the early years, the PRC essentially followed the Soviet model of governance. Despite several political and social upheavals like the Great Cultural Revolution, the Chinese economy essentially followed that of a typical developing economy for nearly four decades. It is indeed a puzzle that starting from the beginning of the twenty-first century, China's GDP surged ahead (Fig. 2). By 2022, China occupied the second position in the world listing, while the USA still led the world. China has clearly shifted to a new, dramatically steeper growth trajectory, very different from the growth trajectories of other developing nations like India, that

too in a short span of twenty years. How did it happen? Are there lessons for other developing countries like India?

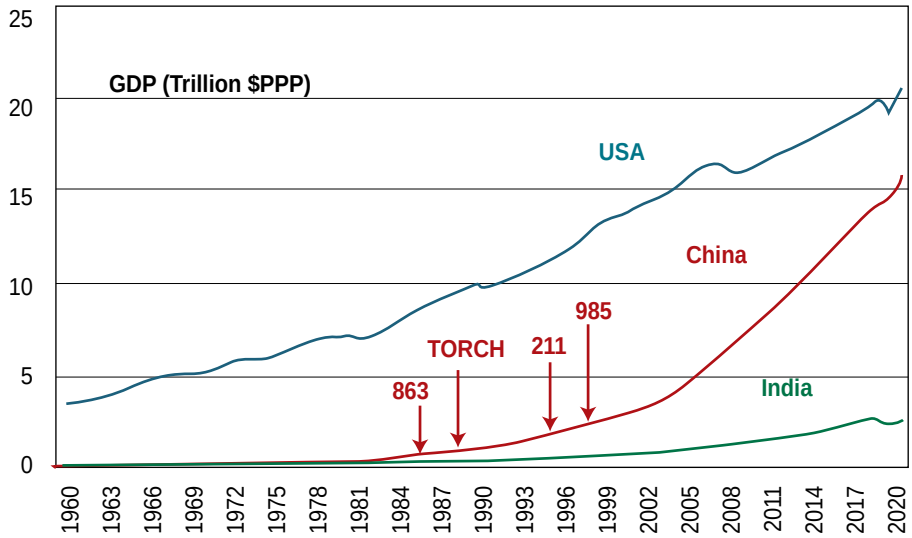

Figure 2: *Growth of Gross Domestic Product of the USA, China, and India, along with some Critical Interventions*

Two early interventions in China were a State High-Tech Development Plan, *Programme 863 (1986)*, to stimulate research and development, not only in the three strategic sectors—nuclear, space, and missile defense but also in a wide range of key Science and Technology areas and a dedicated *Programme TORCH (1988)*, to create ecosystems and infrastructures necessary to support innovation and entrepreneurship amongst Science and Technology professionals. China also recognised early the need to induct more students to take up higher education and research and to strengthen them to internationally competitive levels in the generation of new knowledge by way of publications in refereed journals and the generation of Intellectual Property. This led to two new initiatives—*Project 211 (1995)* to strengthen education and research in about a hundred institutions of higher learning in critical disciplinary areas and *Project 985 (1998)* to create world-class universities as a national priority for the twenty-first century to "enhance the capacity of high-level manpower in the frontier fields of science and technology". These interventions led to a rapid and unmistakable rise in the number of science and engineering graduates in China (Fig. 3).

Did the interventions work? Fig. 3 and Fig. 4 show the growth of first university degree holders and doctoral degree holders in natural sciences and engineering during the early years of the twenty-first century. It is

interesting to note that, while in 2000 Chinese Universities awarded less than half the number of doctorates in STEM as compared to US universities, by 2010 the numbers from China became comparable to

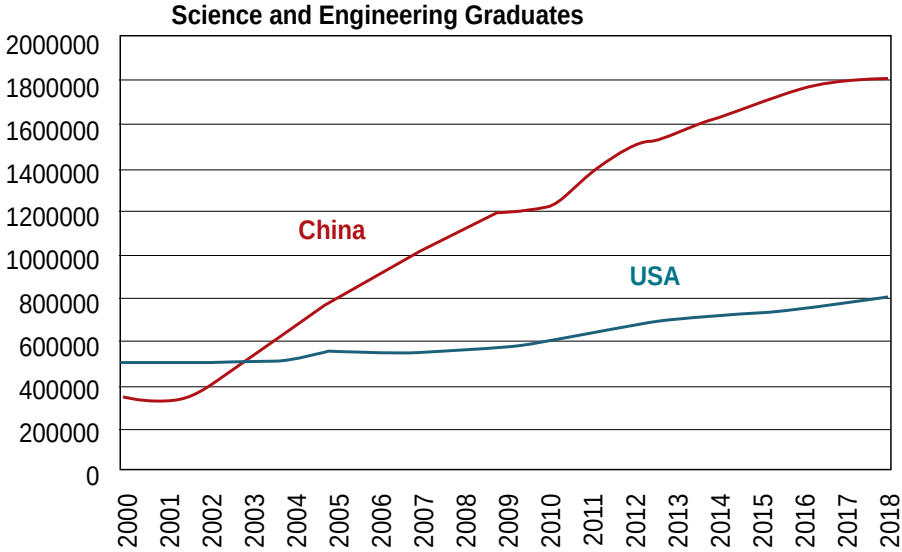

Figure 3: *Science and Engineering Graduates in China and the USA*

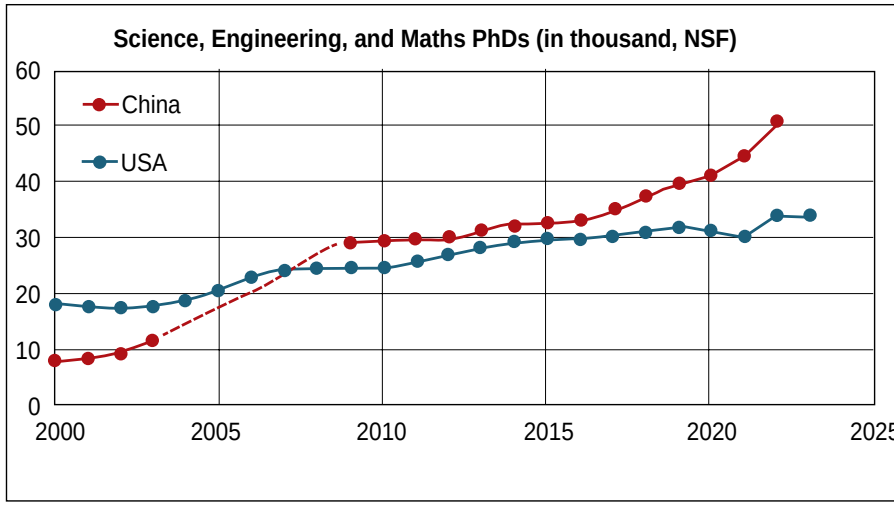

Figure 4: *PhDs in Science, Engineering and Mathematics in China and the USA (National Science Foundation USA)*

those from the USA [2]. Based on current enrollments, it is estimated that by the end of 2025, China will have nearly twice as many STEM

PhD graduates as the United States. It is also reflected in the number of scientific publications by China, which has reached the number one position in this.

China, while making major investments in education, Research and Development, has also been making major investments in building an innovation and entrepreneurship ecosystem to convert technical knowledge into wealth. Together with the market pull sustained by proactive government policies, China is confident of leading the technology-driven world in the coming decades.

Countries like the USA have shown that innovation and entrepreneurship hold the key to drawing economic benefits out of scientific strengths. Silicon Valley and Boston Route 128, mentioned earlier, are well-known examples of this. China ventured into technology innovations and the entrepreneurship bandwagon with the TORCH programme. With support from the United Nations Fund for Science and Technology (UN FS&T), China started the Technology Business Incubation (TBI) programme in Wuhan in 1989. Interestingly, five Indian experts from the Entrepreneurship Development Institute, Ahmedabad, employed by UN FS&T, played a major role in preparing the Chinese program of Technology Business Incubators. By the year 2000, China had established nearly 200 TBIs. At the end of 2016, China was home to 3255 TBIs with a further ambition to increase the number of incubators, including a few incubators overseas. By May 2025, this number had swelled to 16,000 and spread across most of the geographical area of China. About 6-8% of the technically trained people in China are now reported to be involved in some kind of entrepreneurial activity [3].

We believe that the China story holds important lessons for all developing countries of the world, including India.

The Indian story

India is one of the few countries in the world that, on coming out of centuries of colonial rule on August 15, 1947, chose not only a democratic form of governance but also Science and Technology for development. With a population of half a billion people, the majority of them living in villages, facing acute food shortages and poor infrastructure, including educational infrastructure, it was a challenge. It was also an opportunity with its vast young population, eager to learn and raring to propel India to its rightful place amidst the comity of nations across the world. India had always recognized education and research as integral part of its long culture. The very few modern universities established before India became independent at Calcutta (Kolkata), Bombay (Mumbai), Madras

(Chennai), and Allahabad (Prayagraj) in the middle of the nineteenth century taught modern science and produced brilliant scientists like J.C. Bose, M.N. Saha, S.N. Bose, C.V. Raman, P.C. Ray, S. Ramanujan, and Birbal Sahni, to name a few. It was however quite obvious that the educational and research infrastructure that existed at the time of independence were far below the needs of a new found nation. The country, therefore, accorded a high priority to education at all levels right from day one after independence. Several new Universities funded by both the central and the state governments were created across the country. Private institutions and individuals were also encouraged to start new educational institutions. In 2022, India had 42.2 million students across 1168 universities, 45473 colleges, and 12002 stand-alone institutions, according to the All-India Survey on Higher Education, 2024. India also created a number of premier institutes at a globally competitive level—five Indian Institutes of Technology, two Indian Institutes of Management, one All India Institute of Medical Sciences and four Central Universities. These were in addition to the already existing Indian Institute of Science, Bangalore which was already recognized globally.

The agricultural education and research system in India deserves a special mention. When India became independent in 1947, it was a country of acute food shortages, depending critically on food imports. It is to the credit of the scientific and political leadership of those decades that today India is near self-sufficiency, not only in wheat and rice but also in milk, vegetables, etc. Considerable progress has also been made in the manufacturing of generic drugs, affordable vaccines etc. India's achievements in emerging areas of technologies like Atomic Energy and Space are well-known and well-documented. We do miss such successes in other areas of science and technology, in particular emerging areas.

One of the early indicators that all is not well in India's educational system is that, in spite of the different success stories, the number of full-time researchers in the country remains quite low as compared to the rest of the countries in the developed part of the world. As shown in Fig. 5, India has only about 260 full-time researchers per million population. It should also be mentioned that the number of doctoral students in most of the Institutions of higher learning, in particular in the Universities in India, hardly exceeds 10% [4].

In contrast, most of the developed countries have a few thousand researchers per million population. Even China has close to two thousand researchers per million population. In a typical Chinese University, not only does the student strength often exceed several tens of thousands, but *one-third of them are also doctoral students*.

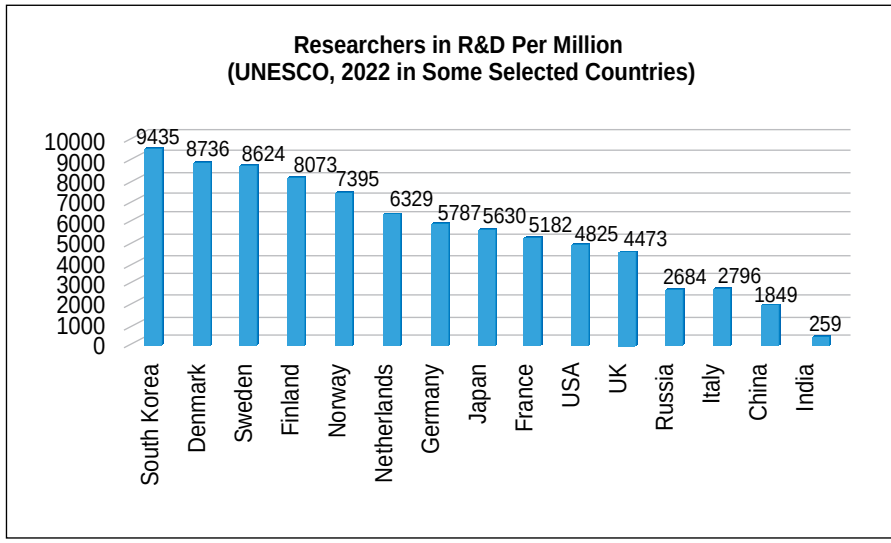

Figure 5: *Number of Researchers per Million Population in Some Selected Countries*

One of the main reasons for the small number of researchers per million population in India is the relatively small number of Institutions of higher learning in India as compared to other developed countries. In particular, the opening of more institutes of higher learning in India was stalled for several decades (see Fig. 6a, 6b, 6c, and 6d). The scarcity of seats in institutes of higher learning and repute has continued to frustrate generations of equally brilliant young men and women and made them vulnerable to exploitation by coaching institutes. It is disturbing

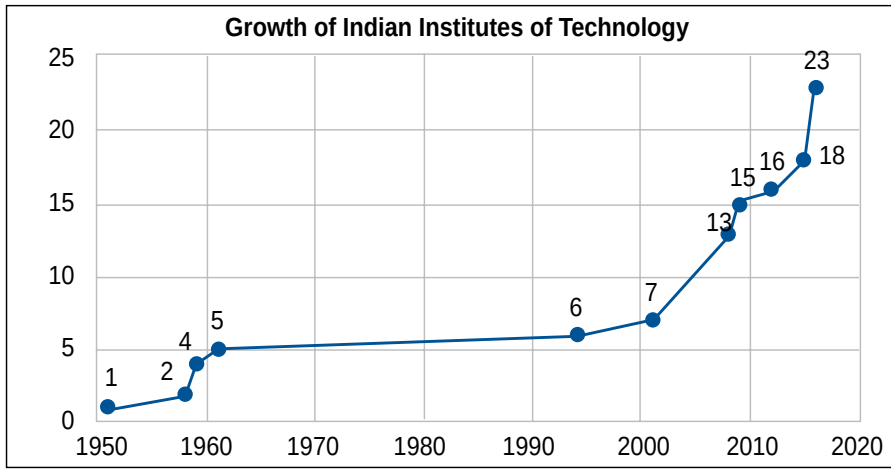

Figure 6a: *Growth of Indian Institutes of Technology in India*

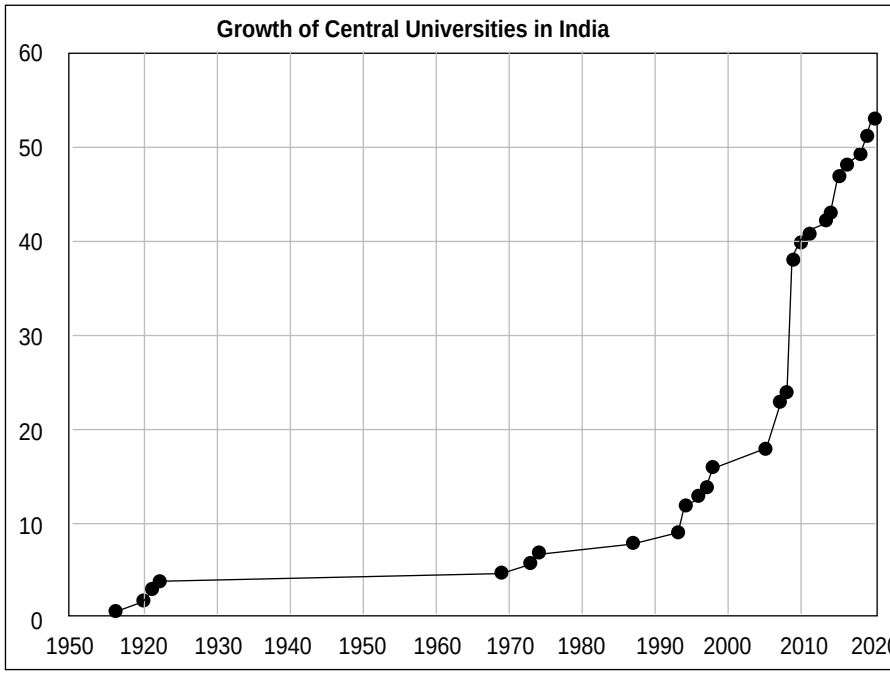

Figure 6b: *Growth of Central Universities in India*

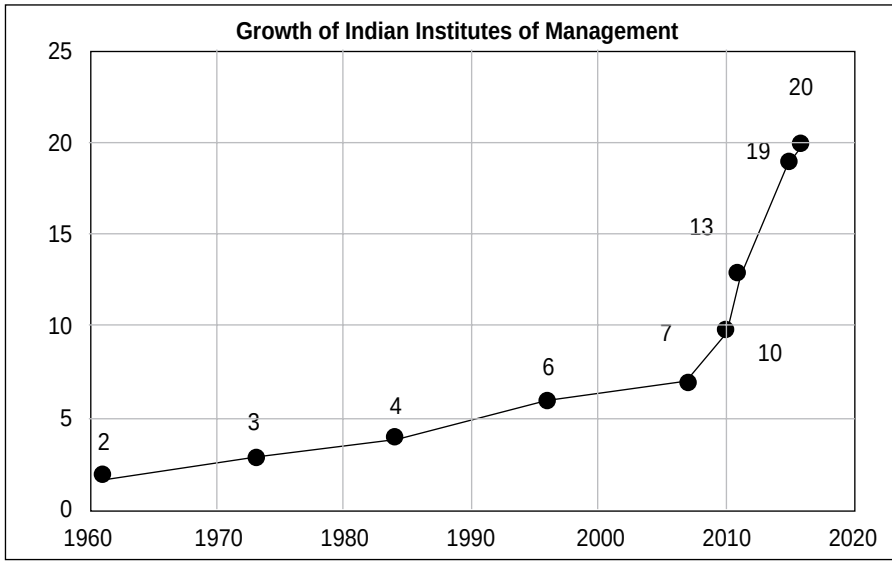

Figure 6c: *Growth of Indian Institutes of Management in India*

to note, for example, that 54,378 students cleared the Joint Entrance Examination—Advanced, which makes them eligible for admission to IITs, the total number of seats available was only 18,160 in 2025.

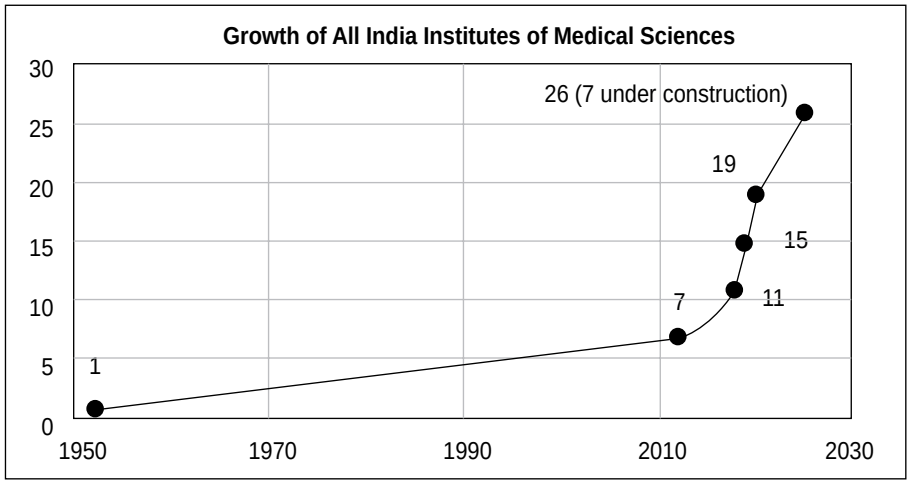

Figure 6d: Growth of All Institutes of Medical Sciences in India

It is greatly satisfying to note the recent increase in the number of premier institutions of higher learning, and we hope that this momentum will be continued.

Another belated step in the right direction is the establishment of Indian Institutes of Science Education and Research along the pattern set by the Indian Institute of Science, Bangalore, to integrate and promote interdisciplinary science, education and research. The National Institute of Science Education and Research, Bhubaneshwar (2006), supported by the Department of Atomic Energy, has a similar mandate. The Indian Institute of Space Science and Technology was established in 2007 at Thiruvananthapuram to promote higher education and research in space sciences, technology, and engineering by the Department of Space. For sure, research laboratories under the Government like the Department Atomic Energy, Department of Space, Department of Agriculture, etc., and many other full-fledged research institutes in various disciplines under CSIR and ICMR are doing globally competitive work.

However, we do believe that the vast majority of excellent researchers in the University system are unable to fully reach their full intellectual potential due to lack of access to expensive facilities and instruments and the country is missing out on their research capabilities. Creation of competitive research capabilities in all Universities is not only time consuming but also is an expensive option.

How to involve more of the faculty and students from Universities and other higher educational institutions in research?

As was mentioned earlier, while the number of institutions offering post graduate education in the country has increased enormously, most of them are under the State governments. Non-government participation in higher education and research in India has also increased substantially in the last few decades. There are several higher education institutions outside the Government system which are making a mark even internationally. Unfortunately, the research contributions from these institutions have only been marginal since investments required to create a state-of-the-art research infrastructure are indeed beyond the scope of the majority of these institutions. The Government is, in general, reluctant to make long-term investment in creating expensive facilities in such institutions.

To enable access to high-end research facilities for the University faculty and students and to encourage research in cutting-edge areas in the Universities, the scheme of Inter-University Centres was initiated about forty years ago with very encouraging results. Two Inter-University centres with a focus on scientific research and technology development deserve special attention.

- **Inter-University Accelerator Centre (IUAC), New Delhi, (1984)**
- **Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, (1988)**

How have they contributed to opening up frontier research and developmental opportunities in our educational institutions?

The Inter-University Accelerator Centre, New Delhi, was the first Inter-University Centre, founded in 1984. The objective of the Centre was to provide, within the university system, world-class facilities for accelerator-based research in focused areas of nuclear physics, atomic physics, material science, radiation biology, etc., in addition to accelerator technology. To start with, the facility was centred around a 15 UD Pelletron, a tandem electrostatic accelerator capable of accelerating ion beams of all essentially stable nuclei with energies up to 200 MeV, purchased off-shelf. A Superconducting Booster Accelerator was indigenously designed, fabricated and added to receive the ions from the Pelletron and further increase their energy. The Centre also has a Negative Ion Beam Facility that provides low-energy, stable, and collimated ion beams (30-200 keV) for material science research through ion-solid interactions, and a high current injector that focuses on accelerating high-intensity beams for applications like the development of superconducting cavities and testing of accelerator components. IUAC has also developed excellent support

facilities for studies in nuclear physics, for research in material science, atomic physics, radiation biology, and accelerator mass spectroscopy. IUAC is also an important participant in the India-Fermilab Collaboration on advanced accelerator systems. The Centre has a user base of more than 300 scientists from universities and colleges, spread across the country. The Centre organises regular schools, workshops, refresher courses, and conferences, both inhouse and in other participating institutions.

The Inter University Centre on Astronomy and Astrophysics, Pune is the national centre for research in Astronomy, Astrophysics, and related areas. Established in 1988, IUCAA has created excellent facilities for research and development in these subjects. IUCAA has its own 2 metre optical and near infrared telescope, is a partner in the 11 metre Southern African Large Telescope—run by an international consortium, and the new Thirty Metre Telescope Consortium led by Caltech, USA. IUCAA also has an excellent library, high-performance computing facilities, a data centre, and instrumentation laboratories, and has facilities like the Virtual Observatory and a highly developed public outreach programme. IUCAA plays a major role in AstroSat, India's first dedicated multi-wavelength space observatory, which has special instruments particularly sensitive to UV and different energies of X-rays. IUCAA is also involved in many other international collaborations, including LIGO. The academic members of IUCAA conduct research in theoretical and observational areas and are involved in the development of advanced instrumentation for astronomy. IUCAA has more than two hundred Associates from universities and colleges, who regularly come to IUCAA along with their research students for collaborative research and to use the facilities. Many university students conduct their research work with members of the IUCAA faculty as co-guides. IUCAA conducts several workshops and other meetings every year on its own campus, as well as on various university and college campuses in the country. IUCAA also has several Resource Centres (IRCs), located in different parts of the country, where resources are created for use by the local and regional astronomy community, and astronomy programmes are supported by IUCAA in universities and colleges. IUCAA programmes have led to a significant increase in the number of university departments where astronomy is taught, and in the number of university and college faculty and students, who are involved in research in frontier areas of astronomy using state-of-the-art techniques.

The two Inter-University Centres are clearly cost-effective, have high impacts and have democratised access to "big science" for university researchers

Yet another initiative to open up high technology facilities under the Government to University faculty and students is the creation of the UGC-DAE Consortium for Scientific Research (UGC-DAE CSR), Indore. The UGC-DAE CSR, Indore, has centres at Indore, Kolkata, Mumbai, and Kalpakkam, and a node at Bhubaneshwar. This Centre aims to provide the university faculty and students with regular access to the big-science facilities of the Department of Atomic Energy (DAE)- namely, the Synchrotron Radiation Sources at Raja Ramanna Centre for Advanced Technology, Indore; Dhruva Reactor at Bhabha Atomic Research Centre, Mumbai; the Variable Energy Cyclotron, the Superconducting Cyclotron, Radioactive Ion Beams, and Medical Cyclotron (30 MeV) and other facilities at Variable Energy Cyclotron Centre, Kolkata, facilities at Indira Gandhi Centre for Atomic Research, Kalpakkam, and Institute of Physics, Bhubaneshwar. The UGC-DAE CSR also has its own laboratories that provide excellent high-tech facilities, which are internationally competitive in material science, condensed matter physics, and other related areas. While providing access to large DAE facilities, the IUC makes important value additions by developing special research capabilities which are accessible to university teachers and students. The UGC-DAE CSR facilities get over five hundred visitors a year from the universities, who carry out original research, which has led to a number (over 200 per year) of publications in international journals. A major thrust has been provided in the last five years through a large range of experimental facilities, with the sample environment allowing studies at high magnetic fields and at low temperatures. These unique facilities have led to many high-impact research publications from the university system.

Given the excellent performance of the existing Inter University Centres, the positive impact that they have on the University system and the emergence of several new areas of research such as Cyber Security, Artificial Intelligence etc., a strong case exists for creating several new IUCs in carefully chosen areas.

One has to also remember that the workforce of tomorrow will have to be ready with skills in these emerging areas too. Are there enough teachers in our colleges and Universities in these areas to train future-ready workers? One can't depend only on the limited number of elite institutions for this purpose. We believe that Universities and colleges will remain the future training grounds and should have strong links with elite institutions. Inter-University Centres offer opportunities for a large number of faculty and students in a large number of institutions

in emerging areas. Initiatives in the past along these lines have been scattered but deserve focussed attention.

Summary

The rapid economic development of the United States of America during the second half of the twentieth century and beyond, and of China in the recent decades, can directly be linked to specific policy interventions by the two countries, putting emphasis on high-quality education, research and entrepreneurship. We note that after independence, while India quickly established several world-class institutes of higher education and research and embarked on a technologically driven journey, the process slowed down subsequently for several decades, severely throttling India's ability to realise its full potential. Noting that the creation of centres in new and emerging areas of research involves both time and resources, greater involvement of existing educational institutions is unavoidable. We suggest that the creation of more Inter-University Centres with centralised facilities and coordinated research programmes for research in the universities and post-graduate educational institutions can lead to a quantum leap in the quality and quantity of research in universities and other higher education institutions. We also believe that with such strategic initiatives, India can substantially increase the quantum of research and the number of researchers in the country and secure its rightful place in the 21st-century knowledge economy.

Acknowledgement

This article is based on years of observations and discussions with colleagues spread across Research organisations and Universities. We are thankful to all of them.

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He served as Director, Institute of Physics, Bhubaneswar, during 1989-1995 and Secretary to the Government of India, Department of Science and Technology (DST), New Delhi, during 1995-2005 and Director of the National Institute of Advanced Studies, Bengaluru, 2009-2014. He was DAE Homi Bhabha Chair in the Inter-University Accelerator Centre, New Delhi (2006-2010), and the Chair of Recruitment and Assessment Board of the Council of Scientific and Industrial Research.

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DINESH K. SRIVASTAVA is theoretical physicist with seminal contributions to physics of relativistic heavy ion collisions, the formation of quark-gluon plasma, and nuclear theory. He served as the Director of the Variable Energy Cyclotron Centre (VECC) in Kolkata during 2012-2016. He was a DAE Raja Ramanna Fellow and a Homi Bhabha Chair Professor at the National Institute of Advanced Studies (NIAS) in Bengaluru and an Honorary Professor at the National Institute of Advanced Studies contributing to programs on energy, environment, and climate change, alongside his physics research. He is a recipient of several technical achievement awards of the Department of Atomic Energy and the Outstanding Referee Award by the American Physical Society in 2009. He was elected to the fellowship of INSA in 2016 and is also a fellow of National Academy of Sciences of India.

Science in India: Current Status, Opportunities & Challenges

Vinod K. Singh

Scope

The use of the word Science is mere semantics. It includes all the branches of science, maths, and engineering. India's scientific enterprise represents both a continuation of its ancient intellectual traditions and an expression of its modern developmental aspirations. From early advances in mathematics, astronomy, and medicine to pioneering achievements in space exploration, nuclear science, and information technology, Indian science has evolved through multiple phases of growth.

Ancient Indian scholars made significant strides in mathematics and astronomy. Among their most influential contributions was the invention of zero and the decimal system, credited to Aryabhata in the 5th century CE. In his landmark text Aryabhatiya, he proposed that the Earth rotates on its axis and offered strikingly precise astronomical calculations. Later, in the 12th century, Bhaskara II expanded upon these ideas, developing concepts akin to calculus long before Newton and Leibniz. In the realm of astronomy, thinkers such as Varahamihira advanced the study of planetary motions and weather phenomena.

In recent decades, the country has emerged as one of the largest global producers of scientific publications and a significant hub for technological innovation. It ranks 3rd globally in the number of publications and 6th in patents filed. In the Global Innovation Index 2024, India stands at 39th. However, despite this progress, challenges remain in terms of research quality, innovation capacity, infrastructure, and global competitiveness. A critical reflection on the current status of Indian science, along with its opportunities and challenges is essential for shaping a stronger research and innovation ecosystem in the years ahead.

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Milestone events in Indian science and key successes

The colonial era, despite exploitation, saw the emergence of formal scientific institutions. The Indian Association for the Cultivation of Science (IACS), founded in 1876, became a hub for scientific inquiry. It was here that C.V. Raman conducted his Nobel-winning research on the scattering of light, now known as the Raman Effect. Another towering figure from this period was Srinivasa Ramanujan, a self-taught mathematician whose work on number theory, infinite series, and continued fractions earned him recognition among the world's top mathematicians. Jagadish Chandra Bose, meanwhile, made pioneering contributions in radio waves and plant physiology, proving that plants respond to stimuli.

After gaining independence in 1947, India prioritized self-reliance in science and technology. In the 20th century, some new universities and institutes were established, and they flourished. One of the first major steps was the establishment of the Council of Scientific and Industrial Research (CSIR) in 1942, which has since spearheaded research in a wide range of disciplines. Creation of the IITs laid the foundation for producing world-class scientists, engineers, and innovators. India underwent the Green Revolution in the 1960s, led by M.S. Swaminathan, transforming from a food-deficient country to one of surplus by introducing high-yielding crop varieties and modern farming techniques. In the early 1970s, the white revolution was initiated to increase milk production sustainably. Promoting fisheries through the blue revolution (1985) and edible oil seeds from the yellow revolution (1986) followed these efforts to achieve self-sufficiency. The 21st century saw yet another academic revolution with many universities and institutes (new IITs, IISERs, NITs, IIITs, new IIMs, new SPAs, new AIIMS and others) being established.

The establishment of the Indian Space Research Organisation (ISRO), one of the most celebrated scientific institutions, in 1969 led to the launch of its first satellite (Aryabhata, 1975), followed by multiple successes using its own launch vehicles (PSLV and GSLV). The strong foundation over the years enabled the country to launch Chandrayaan-1 in 2008, which discovered water molecules on the Moon — a groundbreaking achievement in lunar exploration. Later, the Mars Orbiter Mission (Mangalyaan) was launched in November 2013. It successfully entered Mars' orbit in September 2014, making India the first Asian nation and the fourth in the world to achieve this feat. Recent years have seen the successful landing of Chandrayaan-3 (2023) near the lunar south pole. The same year, India launched Aditya-L1, its first solar observatory to study the Sun. While India is working on its human spaceflight program (Gaganyaan) and reusable launch vehicle (RLV-TD), the overall capabilities have empowered us with satellites for telecommunications, weather forecasting, disaster warning, and an indigenous regional navigation system.

India's advancement in nuclear science began under the leadership of Homi J. Bhabha. The successful test of the first nuclear device in 1974 (Smiling Buddha) and the subsequent Pokhran-II tests in 1998 established India as a nuclear power. Further, defence aviation (Tejas), hypersonic technology demonstrator vehicle (HSDTV, 2020), and aircraft carrier (INS Vikrant, 2022) have added to the repository of technological capabilities.

The country's journey in supercomputing began with its first indigenous supercomputer, PARAM, in 1991. Today, under the National Supercomputing Mission (NSM), India is establishing high-performance computing infrastructure across the country. Furthermore, with the launch of the National Quantum Mission, the country is positioning itself at the forefront of quantum computing and encryption. The last few decades have seen India become a global IT services and software development hub, with companies like TCS, Infosys, Wipro, etc. The current investments in electronics-related infrastructure will make us self-reliant in multiple domains. India's IT capabilities were the key enablers for implementing digital initiatives, including a unique digital identity platform (Aadhaar) and a unified payments interface (UPI) for instant payments.

India's strong capabilities in chemistry have established it as a major player in the global production of active pharmaceutical ingredients (APIs) and generic drugs. Often referred to as the "Pharmacy of the World," India's robust generic drug industry has gained international recognition. During the COVID-19 pandemic, we successfully developed an indigenous vaccine and produced others, such as Covaxin and Covishield. Millions of doses of these vaccines were exported under the Vaccine Maitri Program. In recent decades, deep-tech healthcare solutions utilizing chemistry and biotechnology have attracted the attention of policymakers. While we have made significant progress in areas such as DNA fingerprinting technology, gene therapy, and polio eradication, there is still much work to be done. Continued strategic support for the development of indigenous biotechnology and biopharmaceutical production capabilities is an important step in the right direction.

India is actively engaged in international scientific collaborations. It is a member of major global projects such as CERN, ITER, and LIGO. India joined the Artemis Accords in 2023 to promote peaceful space exploration and continues to lead climate initiatives like the International Solar Alliance.

Areas where improvements could have been and should be made

There remains considerable scope to enhance and fully leverage India's scientific capabilities and opportunities. Ensuring adequate and sustained investment in research and development across critical scientific domains is essential. However, India's R&D expenditure (~0.7% of GDP) is far lower than that of leading economies, and remains a major concern. In addition, rigid funding structures, strict divisions between recurring and non-recurring allocations, and delays in grant disbursement have significantly impeded research progress. Compounding the challenge is the relatively low contribution of the private sector, which limits the nation's overall research capacity. Addressing this requires not only an increase in budgetary support from both government and industry but also the adoption of systematic strategies to direct efforts across interconnected scientific domains. Parallel attention must be given to bridging infrastructure gaps and strengthening human resources. Equally important is addressing the disconnect between school education and higher learning, so that future generations are inspired to pursue and contribute to science. Alongside this, creating opportunities to retain talent and reduce brain drain is essential for building a robust and sustainable scientific ecosystem.

The evaluation system of research performance needs major improvement. Overemphasis on publications and citations has led to a "quantity over quality" culture. The parameters used to evaluate professional growth in science require substantial reform. While the scientific community is encouraged to pursue discoveries and innovations, the limited number of researchers in many fields naturally results in fewer publications and citations [1]. However, since institutional rankings heavily emphasize such metrics, administrators often prioritize quantity over quality. This raises a critical question: how can we establish robust internal peer review systems that truly reflect scientific merit? A similar challenge exists in the domain of intellectual property rights. Despite institutional support, shortcomings in patent quality and insufficient national phase filings reduce the commercial potential of innovations. This situation is unsurprising, as many decision-makers on such committees acquire expertise only while on the job. Structured training for administrators, along with targeted reforms, can help close these gaps—unlocking the full potential of indigenous innovation and enabling more effective translation of research into real-world applications.

The same challenges extend to the deep-tech entrepreneurship ecosystem. While it is widely acknowledged as a high-risk, high-investment, and high-return domain with longer gestation periods, expectations often overlook the time and nurturing required, seeking outcomes before providing adequate support.

Policy gaps have similarly hindered research infrastructure. Although substantial investments have been made to establish national facilities and acquire advanced equipment, the lack of skilled human resources limits their optimal use. With the right expertise, such facilities could significantly accelerate interdisciplinary and translational research through stronger collaborations.

To address these challenges, the government has launched several initiatives. The Anusandhan National Research Foundation (ANRF) has been set up to fund research and strengthen public–private partnerships, while the National Deep Tech Startup Policy (NDTSP) aims to build a comprehensive ecosystem for deep-tech innovation in the coming years [2]. In addition, targeted efforts are underway to promote the growth of specific innovation-driven sectors.

The current state of Indian science, including your field

India has made a significant contribution to the growth of science, as it is reflected in our ranking. Globally the country ranks 3rd globally in the number of publications, 39th in the Global Innovation Index (2024), and 6th in intellectual property (IP) filings. Indian growth in Science and Technology is also reflected in India's deep tech sector, with a large number of startups focusing on areas like AI, quantum computing, biotechnology, and materials science. The government supports these initiatives through the National Deep Tech Startup Policy (NDTSP).

The Government of India, through the Department of Science & Technology (DST), established the National Mission on Interdisciplinary Cyber Physical Systems (NM-ICPS) to foster interdisciplinary cyber-physical technologies like AI, Robotics, cyber security, and IoT. The mission established 25 Technology Innovation Hubs (TIHs) across the country to drive technology development, entrepreneurship, and international collaborations, aiming to make India a global leader in these critical domains.

A few recent efforts have supported advancements in various areas. In 2015, the Government, through the Ministry of Electronics & Information Technology (MeitY), launched the Digital India program with the vision to transform the country into a digitally empowered society and knowledge economy. The same ministry is supporting other mission programs like the National Program on Artificial Intelligence and the Semiconductor Mission. The other important program launched by the Government through DST is the National Mission on Quantum Technology & Applications. The mission has set up thematic hubs in academic institutes to work on quantum computing, communication, sensing & metrology, and materials and devices. In order to make the

country a global hub for the production of green hydrogen, the Ministry of New & Renewable Energy (MNRE) of the Government launched the National Green Hydrogen Mission. This will make the country *Aatmanirbhar* (i.e. self-sufficient) through clean energy. The Ministry of Earth Sciences (MoES) launched a Deep Ocean Mission to develop technologies for deep-sea exploration. There had been other initiatives, such as the National One Health Mission and the biotechnology sector for healthcare and agriculture. Some other efforts are in the pipeline, such as the National Livelihood Mission, Carbon Capture Utilisation & Storage, and Cell & Gene Therapy.

Some of the above missions have benefited immensely from the nation's strength in chemical sciences. This field has always been a central science, and is continuously fine-tuning itself to meet the new norms of sustainability. Additionally, it supports the indigenous growth of advanced materials for diverse segments. The government is promoting domestic API manufacturing to reduce import dependence by production-linked incentive (PLI) and a scheme for promoting bulk drug parks. The CSIR laboratories have helped the growth of pharmaceutical industry of the country and has played a pivotal role in providing affordable generic medicines.

Three years ago, the Government of India launched a digital platform, MANTHAN, to engage all stakeholders in collaborative work for national development and sustainable development goals. This is a very useful initiative which will help our various schemes.

The leitsätze (the guiding principles) for academia

The core guiding principles for doing better science (towards academic excellence) revolve around quality manpower (*including the quality of the Head of the organisation*), relevant research areas, and effective governance. A study by A.H. Goodall [3] suggests that a University performs better with a scholar-leader. So, mediocrity should be avoided when appointing a Director/VC. However, this alone is not enough. The effective governance system should also exist to provide freedom for academics, but with accountability. These require both structural principles (how institutions function) and cultural principles (how individuals and groups work together).

The Hon'ble Prime Minister has consistently underscored the importance of improving the 'Ease of Doing Science' in the country. As a proud citizen of the country, it is our responsibility to adhere to his call. We are the people involved, as heads of institutions and funding agencies, who should be sensitive to the needs of researchers. While seniors are able to carry on their work, new researchers quite often struggle in

the beginning. It is the responsibility of the academic organization to provide them with basic infrastructure and a reasonable seed grant. The bottlenecks, such as the delay in fund disbursal from the funding agencies (ANRF, DST, DBT, CSIR, etc) and obstacles in purchase procedures, should be addressed.

There is a need for schemes with incentives for researchers so that they keep on getting motivated. Some of the schemes, like the Swarnajayanti Fellowship and the J.C. Bose Fellowship of the erstwhile SERB (now ANRF), were very effective in motivating researchers towards research. These schemes should be revived.

An effective evaluation system for teaching, research, translational work, and administration is the need of the hour. There should be an emphasis on 'quality' rather than quantity for the evaluation. It is a healthy thought that faculty/scientists should have academic freedom, but it must come with responsibility and accountability. This is why Academic organisations should adopt a tenure track system for recruiting faculty/research scientists. It will bring in productivity and seriousness. In fact, the 7th CPC has a provision in the office order of the Ministry of Education that says, "*The Institute should put in place a process for discontinuation of non-performers*".

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11

India to be a Developed Nation by 2047 — the Role of INSA

Indranil Manna

Scope

India has a rich history of contributing to global enlightenment and its considerable scientific capabilities. However, with a population of 1.45 billion, the per capita economic and social advancement remains relatively limited. To restore its past distinction and progress toward becoming a Developed Nation, it is essential to consolidate resources and engage in dedicated and sincere efforts aimed at empowering the vast population. This can be achieved through the promotion of quality education and the application of scientific methodologies, thereby transforming challenges into opportunities.

India —From an ancient civilisation to a modern nation

India is not only one of the oldest civilisations with over five thousand years of known history (over two thousand years of chronicled and another three thousand years of anecdotal and indirect sources), but it also used to be among the richest nations until the early 18th Century. No wonder India attracted travellers, traders, scholars, and rulers from several neighbouring and distant countries, some with genuine academic interest and some others purely for the lure of wealth and prosperity. In the distant past, India nurtured the top seats of learning like Taxila (~1000-500 BCE) and Nalanda (427-1400 CE) and was privileged to have gifted seers and scholars whose contributions are revered even today. Kanad (~2nd century BCE) was known to have delved deep into the origin of matter and first coined the concepts of '*Anu* (molecule)' and '*Paramanu* (atom)'. Aryabhatta (476-550 CE is credited with pioneering the concept of pi (π), zero, and the decimal system. Charak (~2nd century BCE) was the father of Ayurveda, the science of medical treatment using the extracts from nature. Susruta (~6th century BCE), the surgeon in ancient times, is credited to have practised cataract and plastic surgery. Even during the period of British rule (1757-1947), despite utter poverty,

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exploitation, and discrimination, science in India flourished with the likes of J.C. Bose, S.N. Bose, C.V. Raman, Meghnad Saha, and many more, who pursued the sciences of the higher order. Their science was acknowledged by the international scientific community, either during their lifetime or often much later. Currently, India is not only a mighty economic power with the fourth largest nominal GDP in the world, but it has also earned the respect of the international community for its successful Mars and Lunar mission, commercial satellite launching capability, nuclear energy harnessing expertise, successful missile, drone and air defence technology, and many more stellar achievements. These are strategic areas where international help and cooperation are unlikely, and indigenous development is the only option. India is a food-surplus nation. The current level of life span expectancy and child mortality or survival at birth is comparable, or better than the world average. In the technological field, India is the largest manufacturer of drugs and pharmaceutical products, the second largest manufacturer of steel, cement, coal, and food and agricultural products, and the third largest producer of electricity. India is seen as the third largest civil or real estate market, fourth largest automobile manufacturer and mining potential, and ninth largest aviation sector. The annual GDP growth in India is among the highest in the world.

The current scenario

There is no denying that the flip side of India's growth and prosperity is rather dark, even embarrassing, and poses a major impediment to its rapid economic and societal progress. India is a land of diversity with 28 states, 9 union territories, 22 official languages (with nearly 2000 dialects spoken as mother tongue), and 8 major religions practiced by various sections. It comprises a large range of climate and seasons, food habits, attire and dress codes, physical appearance and built, social and religious customs, languages and letters, altitude and geographical terrains, natural and mineral resources, and even anthropological evolution. India was never a monolith but a subcontinent with varieties as rich and diverse as those in Europe or Africa. However, in the words of Rabindranath Tagore, India has been a land of unity in diversity.

In terms of economic and developmental parameters, India is placed in a rather poor position despite being a $4.2 trillion economy. India occupies 142nd position in per capita income, 134th in the Human Development Index (HDI), comprising health, education, and living standards, 38th in the Global Innovation Index (GII), and 62nd in the quality of life ranking. Despite efforts by the successive governments, the Gross Enrollment Ratio (GER) stands at less than 20% at the tertiary level.

Only 14 % of the population in the employable age group (25 to 64 years) carries a bachelor's degree or higher. India is mired with monumental challenges related to poverty, hunger, water, power generation, pollution, health care, unemployment, and security threats (both physical and cyber). The trade deficit (export minus import) is over $200 billion a year, with the GDP-to-debt ratio surpassing 50%. Besides these parametric reflections, India, with its 1.45 billion people, is not only the largest but also the youngest population in the world, with an average age of 28 years. Therefore, it is only logical that this vastly young population will aspire to have a better standard of living, access to education, safer and healthier life, affordable habitat and sanitation, easier mobility and faster transportation, better security and protection against external and cyber threats, a healthier environment with clean air and potable water, and acceptable quality and quantity of food and nutrition. The list is long, and hence the challenges are also humongous.

The role of Science-Engineering-Technology

In the present era of a knowledge-driven economy, India should not only rely upon new knowledge generation and its dissemination through publications and patents but also be competent to exploit that knowledge and convert it into usable products for both economic and societal benefits. This calls for a major drive to convert the exploits of scientific pursuits into technological advantage and economic progress. The Goddess of Learning has no enmity with the Goddess of Wealth. Both fundamental and applied sciences need to flourish in synergy, which leads to translational initiatives that can simultaneously facilitate commercialisation and monetisation of the outcome of science as new knowledge emerges. Otherwise, the clarion call of the Honourable Prime Minister for '*atma-nirbhar*' or self-reliant Bharat will remain only a wish or a distant dream and never be realised. While science needs to continue exploring the conceptual space (as an exercise of "know why?"), its engineering dimension must be consciously explored assiduously to convert the new science into solutions for societal benefits and their sustainability. Areas, like agriculture, medicine, energy, water, climate, and education, need such a translational approach. Engineering is all about finding viable solutions to national challenges and answers to human aspirations without compromising the ethical, moral, environmental, and societal norms and impacts.

We have reasons to be proud in landing the Vikram lander on the southern hemisphere of the moon, marking a distinguished feat that is globally acknowledged and hailed as truly a pioneering achievement. However, similar success stories of pioneering contributions are rather few

in this country. In other words, one wonders why technology development, which one may simplify as "what sells in the market," is not as resplendent as our record in science (know why) or engineering (know how). This gap possibly is a fallout of our current academic practices and success parameters pursued both in academia and R&D organisations. Similarly, in the corporate sector, the sole attention on the balance sheet and profit margins has denied us the opportunity of emerging as a technological leader. As a nation, we have been averse to taking risks in innovation pathways for fear of failure. History is replete with examples of multiple failures eventually leading to a monumental success, and therefore, there is a dire need for a recalibration or revision of our mindsets. Success without prior setbacks is not impossible, but it is neither common nor sustainable.

Education and research — the reality

Nelson Mandela said, "Education is the most powerful weapon which you can use to change the world". If India, with the largest and the youngest population in the world, truly aspires to harness its demographic dividend, education is the only logical course. Education that liberates from prejudices and bias, and allows, in the words of Vivekananda, *the manifestation of the perfection already in man.* In the modern world, education is technology-dependent and hence is expensive. In this regard, many of us lament that despite the Government's resolve to enhance the budget allocation for education up to 6% as per the National Education Policy 2020, why is the outlay limited to 4.6% of India's GDP? A large fraction of this expenditure is consumed by the primary and secondary education. However, technological progress depends on our investments in research and innovation. For reasons difficult to fathom, the spending on Research and Development (R&D) for decades has remained at a paltry 0.65% of the GDP. This miserly approach defies logic on the face of the reality that Israel and the Republic of Korea spend 5.6% and 4.9% of their GDP on R&D, respectively. Finland, a country with a-fifth of the population of the city of Kolkata, occupies seventh position in GII, in comparison to India's rank at 38th. Similarly, the Republic of Korea, which attained independence around the same time as India, with nearly a third of India's population, is the fourth most innovative nation in the world today and files an order of magnitude more patents than us. The export of goods and services in Korea amounts to 44% of its GDP, which was only 2.6% 50 years ago. One steel plant in Korea alone produces 40 million tons, which is nearly one-third of India's annual output today.

While we have done reasonably well in terms of reducing our reliance on fossil fuel for power generation from nearly 60% just a decade ago to

less than 50% now with 30-35% of electrical power now generated from various renewable sources like hydro, wind, solar, and biomass, India's share of energy coming from nuclear power plants is less than 2%, despite India achieving the status of nuclear energy harnessing capable nation over fifty years ago and widely considered a top knowledge-base in fast breeder technology. In comparison, the share of nuclear power to the total energy consumption in France, Ukraine, Finland, Korea, the USA, and the UK is 70%, 55%, 40%, 30%, 20% and 12%, respectively.

The present world order is increasingly becoming transnational. In areas of strategic and commercial interests, no nation can or will help address our needs as a goodwill gesture. There is no free lunch anywhere. gesture. If we can be world champions in cricket both in men's and women's category, and at the same time be the 3rd largest producer of publications in peer-reviewed scientific journals, it is only logical to expect that India should be able to provide sustainable solutions to the challenges in education, energy, water, climate, manufacturing and in all areas that matters to the welfare and dignity of its people.

Role of INSA

The Indian National Science Academy (INSA), founded in 1935, is regarded as the topmost peer group in science in India, comprising the most accomplished and celebrated scientific minds in the country across all scientific branches, including medical, engineering, and interdisciplinary domains. INSA is funded by the Government through the Department of Science & Technology (DST). Suffice it to say, INSA is so prestigious and coveted that every scientist in this country, across the disciplines and in all age groups, aspires to be a Fellow of INSA. However, to a commoner, a pertinent question will be – what does INSA do? Besides recognizing and electing the most distinguished scientists as Fellows through an extremely rigorous multi-tier scrutiny and peer-review process, INSA promotes the mission of science, creates policy documents, promotes the culture of scientific ethics and temperament, trains the youth for scientific leadership, administers government schemes of international travel and national conference supports, publishes journals, edited volumes, and thematic monographs in specific scientific areas, facilitates international collaboration programs, runs a post-doctoral or pre-faculty nurturing scheme (INSPIRE), and offers scientific advice to the government departments/agencies on specific occasions. But that is not enough, especially when the country is aspiring to emerge as a developed nation in two decades from now. Scientific intervention and leadership must play a crucial role in realizing that ambition.

The USA is always regarded as a leader in science and technology (S&T) across the globe, not only because of its volume of publications, number of Nobel laureates, the quality of scholarship on display in nearly 5000 universities, and the globally accepted technologies created are far greater than any other nation, but also it is widely acknowledged that the USA always thinks ahead and leads in all scientific pursuits. At the beginning of this millennium, the USA constituted a high-power committee headed by the then Secretary of State, with fifty experts from thirty different countries to define the most important challenges that humanity must address for global development and progress. The outcome came to be known as the Grand Challenges, comprising fourteen specific targets that succinctly summarized the most important S&T objectives that would affect the entire civilization in the twenty-first century. Several countries either partnered with the USA or independently pursued these grand challenges. It is important to note that the implementation of the grand challenge initiative was not done by the US government but was steered by the National Academy of Engineering (NAE), USA, on behalf of the Federal Government. A delegation from the Indian National Academy of Engineering (INAE) visited and interacted with the NAE in 2013 and explored the possibility of collaborating or replicating the same for India. Eventually, it was decided that India would define and pursue the major technological challenges on its own because the S&T readiness and strategic interest were not the same between the two countries. In this regard, a unique initiative was launched by the MHRD, now the Ministry of Education, called Impacting Research Innovation and Technology (IMPRINT), which was inaugurated by the Hon'ble Prime Minister and the President of India on 5th November, 2015 at the Rashtrapati Bhawan. IMPRINT addressed the entire domain of engineering and technology, aiming to develop prototypes, models or pilot-scale activities to address specific challenges distributed in ten engineering domains primarily through research initiatives spearheaded by the national institutes like IITs and NITs in collaboration with the concerned Government Departments, R&D laboratories, and industries. While IMPRINT-I was steered by the IITs with IIT Kanpur as the National Coordinator, IMPRINT-II was conducted by the combined efforts of the DST and INAE. The outcome was certainly very encouraging because over fifty models and prototypes were developed and demonstrated in an exhibition at IIT Delhi in August 2019 to showcase the progress made by this unique national initiative. Many of those eventually were commercialized. IMPRINT was unique because it aimed only for translational research, addressed the entire spectrum of the engineering challenges and domains (and not one single product or area), allowed all IITs and Higher Education Institutes (HEIs) to participate and collaborate along with the concerned

government departments and industries, and most importantly, was devoted to not just generating knowledge or publications, but developing real technological products and process, or at least, models, prototypes and pilot scale units.

India needs to harvest renewable energy (solar, wind or hydro) in a much larger proportion with higher efficiency. Construction of roads, buildings, airports, stadiums, and several other types of civil infrastructure must be built at an affordable cost, employing indigenous materials and design, and through sustainable means. Transportation should slowly but surely rely more on rechargeable batteries and other storage devices than those relying on fossil fuels and internal combusting engines. Production of steel must reach 300 mt, or even 500 mt, without using or minimizing the consumption of coke by combined usage of hydrogen and natural gas for reduction and extraction. Carbon dioxide emitted by steel and cement plants, agro and chemical industries, and thermal power plants must be captured and sequestrated. Special materials like lithium, rare earth elements, zinc, molybdenum, and tungsten must be recycled and reused rather than relying only on extraction from primary resources. The contribution of manufacturing to our GDP is less than 15%, which the Hon'ble Prime Minister desires to reach 25-30% by 2030. Manufacturing must slowly adopt more of the additive routes than the conventional and subtractive methods. Nearly the entire volume of semiconductor materials and devices is imported. The same analogy applies to the sophisticated military hardware, aerospace components, automobile spares, and specialty glasses. Nearly every single instrument, device, and implant used for medical treatment, including testing and monitoring, is of foreign origin. The laboratories in the Universities primarily depend on microscopes, spectroscopes, measurement kits, software, databases, and devices that are all imported. While import substitution is on the rise, we are far away from claiming ourselves to be technologically self-reliant. In the era of AI & ML, new approaches are needed for technology development.

Given the above scenario, it is not only desirable but highly imperative that national academies like the Indian National Science Academy (INSA), comprising the topmost scientific talents in the country, come forward and offer their wholehearted services to the national cause with enthusiasm and commitment. In my humble opinion, INSA should brainstorm and define the most important scientific and technological issues cited above. INSA should not only define but also roll out a realistic roadmap with a strategy, time limit, and milestones on how to pursue those objectives. As we say in academia, a problem defined is half the problem solved. The policy document created by INSA may be appropriately utilised

with adequate financial support from the government funding agencies, supplemented by the concerned industries, and distributed to academic institutions, R&D laboratories, strategic sectors, and industries of diverse sizes and capabilities to pursue and implement them within a pragmatic time limit and set success parameters. INSA can play a leading role, like INAE did for IMPRINT, in implementing these projects by vetting, selecting, monitoring, and assessing with the single criterion of merit and competence rather than any other yardsticks or regulatory compliance. It is time that the country allows the private sector to participate in nation-building in equal measures as the government-funded institutions with equal partnership and stake.

Concluding remarks

India enlightened the world in the distant past. If we wish to regain that pristine glory, we as a nation must pull all our resources together and rally behind the national goal of emerging as the *Viksit Bharat* or a Developed Nation, sooner than later, with utmost dedication, sincerity and honesty. Let us remember that the challenge in India does not lie in the numerator, but in the denominator, the 1.45 billion people, which is why, despite being the fourth largest economy, most of the economic and social progress indices per capita reflect poorly on India. To turn this apparent challenge into an opportunity, the population must be empowered through true education and scientific approaches. In that journey, let us follow what the Mahatma said, "*Be the change that you want to see around you*".

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Education, Research and Ethics

Talented Scientists, Robust Foundational Research, Innovative Science Communication, and Strong Ethics: Essential Cornerstones for the Future

Chandrima Shaha

Scope

India's advancement toward self-reliance, economic growth, and global competitiveness relies on a robust science and technology sector. Strengthening this sector requires a highly skilled workforce, which in turn depends on increased participation in science-related disciplines. Effective strategies should prioritize early motivation at the grassroots level to encourage engagement in scientific research. Integrating contemporary technological tools into science communication for Gen Z and Gen alpha is essential for effectively addressing new challenges and motivating future generations to engage in scientific careers. Promoting diversity within research teams is also crucial for fostering the exchange of diverse perspectives in scientific research. In addition to inspiring future scientists and enhancing diversity, India would need to develop a comprehensive knowledge base to support upcoming discoveries and innovations, thereby advancing self-reliance in science and technology. Upholding integrity in scientific research is essential to maintain ethical standards. Ongoing policy development and sustained public engagement are fundamental for fostering public trust in scientific research.

Introduction

Over the past five decades, science and technology have significantly transformed society. Research breakthroughs now address critical

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challenges, including food security, public health, environmental threats, and national defence. In recent years, Indian science has contributed innovative ideas, fostered entrepreneurship and developed scientific talent. Despite these achievements, India continues to face substantial challenges and needs to continually adapt to emerging trends. The country improved its position in the Global Innovation Index from 81st in 2015 to 40th in 2022. However, investment in research and development (R&D) remains below 0.7% of gross domestic product (GDP), even though the total R&D expenditure more than doubled from Rs. 60,196.75 crore in 2010-2011 to Rs. 127,380.96 crore in 2020-21. The government has yet to establish a target to increase R&D spending to at least 1.5% of the GDP by 2029, which is essential for sustained progress. This article examines four critical areas: enhancing science communication, strengthening the foundations of basic research, promoting gender-balanced leadership in science, and upholding scientific integrity, leaving aside topics on translational research that I am sure will be discussed by others. These pillars are fundamental to advancing Indian science. While the government has introduced several initiatives in these domains, further expansion and strategic refinement are necessary.

Skilled scientific manpower: the root of research and development efficiency

India's ambition to reach a $30 trillion economy by 2047 requires a strong scientific workforce across various sectors, including policymakers, educators, researchers, innovators, entrepreneurs, and industry leaders. With only 255 scientists per million people, as reported by the Principal Scientific Advisor's office in 2023 [1], the government faces significant challenges in increasing the number of qualified professionals for research roles. This shortage is further exacerbated by students' growing preference for computer science and management. To address these gaps, policies must prioritize job creation and filling current vacancies. The existing scarcity of positions often causes students to choose alternative career paths. While supporting startups is beneficial, it does not offer a complete solution.

The government has launched several programmes to encourage students to pursue science, but these efforts remain insufficient. Building scientific capacity should begin at the grassroots by fostering curiosity and interest in scientific inquiry. Existing initiatives require comprehensive reforms and expansion to engage more students and develop a strong base of trained researchers. Research trainees should be mentally equipped to work collaboratively and across disciplines, as scientific progress today relies more on teamwork rather than individual efforts. The ongoing

development of state-of-the-art research facilities is also essential. To maximize the effectiveness of scientific institutions, universities and colleges, the recruitment of highly skilled professionals is necessary.

A summary of suggestions is provided below.

1. Revise existing government initiatives to promote interest in science by expanding their reach and improving their impact through net increase of existing efforts.
2. Develop targeted programmes to promote interest in scientific disciplines within grassroots communities.
3. Establish advanced research facilities to boost the number of scientists involved in the advancement of scientific innovation.
4. Offer training to help young scientists participate effectively in collaborative and interdisciplinary research by involving scientific institutions across the country.
5. Increase the autonomy of research centres and reduce bureaucratic constraints within universities to create a congenial ecosystem to augment the capacity of these institutions to attract, nurture and retain talent.

Science communication strategies: a vital step to develop scientific manpower

Trust plays a critical role in the relationship between science and society. Policymakers rely on scientists for reliable data to inform decisions on public health threats [2]. Building on suggestions above, this section outlines strategies for effectively communicating science to the society and to the next generation. Traditional sources of scientific information have given way to digital platforms, particularly as smartphone use among young people in Indian cities has increased. The key question is which educational formats best engage digitally native generations. Engaging Gen Z and Gen Alpha is crucial for developing India's future scientific workforce. Surveys show that 94% of Gen Z prefer experiential learning, driving demand for interactive platforms and mentorship. However, 52% are dissatisfied with the current education system, and 36% worry about costs [3]. Gen Alpha, fully immersed in digital technology, demonstrates high technological proficiency and values flexible, hands-on, and personalized learning experiences [4]. Despite their digital fluency, both groups value technology that involves direct human interaction. Scientific institutions can meet these needs by enhancing student engagement through in-person and virtual initiatives. We note that a flagship initiative of the Ministry of Culture, Government of India, SPoCS (Scheme for Promotion of Culture of Science) is designed to foster scientific temper

and awareness nationwide, with a particular focus on students [5]. Such initiatives are essential for promoting a culture of science, and the number of these ventures should be replicated manifold.

The education system must adapt to technological and pedagogical advances at all levels while emphasizing critical thinking to support students' cognitive growth. Competitive scholarships provide vital financial support and recognition for aspiring scientists from Generation Z and Alpha. It is also essential to ensure that education remains inclusive and accessible to students from various backgrounds. As educational materials evolve, continuous teacher training and professional development are necessary to maintain effective teaching methods. India's high level of digital literacy offers a strong foundation for creating effective online science games and problem-solving platforms. Among the 15–29 age group, 97.1% use a mobile phone [6]. Therefore access to this population through interactive platforms is possible.

Generally, to develop a scientifically literate population, strengthening the science communication ecosystem is crucial. To achieve this, the government would need to expand specialized courses in science communication and science journalism at both the undergraduate and graduate levels. Alongside this, policies should be created to incentivize universities and media organizations to recruit and train science communicators. This can help bridge the gap between scientific research and public understanding. Lastly, incorporating the history of the development of science into curricula can further enhance students' understanding by demonstrating that scientific discoveries arise from dynamic processes of inquiry and experimentation. A summary of the suggestion is included below:

1. Develop engaging digital educational materials that spark interest and understanding. Incentivize such efforts.
2. Implement personalized learning strategies that cater to the individual aptitudes, needs and learning styles of each student.
3. Design modules that facilitate hands-on training for enhanced practical experience.
4. Adopt measures to reduce the cost of higher education and increase accessibility.
5. Establish competitive scholarships to support students at each stage of academic progression.
6. Provide ongoing professional development for science teachers to keep teaching methods current and effective. Develop an IT mechanism such that they can keep updates using the One Nation

One subscription mechanism.

7. Offer courses in science communication and journalism to prepare students for public engagement roles.
8. Integrate the history of the development of scientific enterprise into the curriculum to deepen understanding of the manner in which science progresses.
9. Promote citizen science initiatives to encourage public participation in scientific research through programs such as data collection with the help of scientists, data analysis, monitoring changes etc, that will involve the public in scientific activities, thus enabling larger public literacy about science.

Scientific manpower: appropriate balancing

A mix of senior and junior scientists, mentors, gender representation, people with special needs, and diverse geographical backgrounds is essential for true inclusivity. Institutions should implement targeted recruitment and follow merit-based selection *sensu-stricto* to ensure equal opportunities for everyone. This approach would maximize the country's scientific potential. Although women make up over half of STEM university students, only 18.3% hold senior leadership positions [7]. Closing this gap requires focused actions throughout education and career development. Efforts should encourage girls' interest in science and educate parents about opportunities. Schools and institutions need to set clear and unambiguous gender equity goals, create mentorship programs, and formally acknowledge women's contributions. Peer networks and leadership training further support women's career advancement. Policy reforms would need to emphasize gender awareness and provide targeted support and facilities for women faculty. Leadership at all levels would need to regularly evaluate and update strategies to ensure continuous progress. Balanced representation fosters innovation and enhances institutional excellence. Here are some suggestions:

1. Implement initiatives for the education of parents so as to foster equal opportunities for boys and girls. This would require strengthening collaboration between schools and families, with a focus on encouraging girls to pursue science careers.
2. Establish clear targets for gender equity in scientific and administrative roles to enhance institutional competitiveness and support innovation.
3. Comprehensive mentorship programs should be created to support women's professional growth.

Basic research: building the knowledge base

Abraham Flexner, an influential American educator, argued that curiosity and unexpected insights can break down intellectual barriers, leading to transformative ideas and technologies. Michael Faraday's discovery of electricity exemplifies such a breakthrough. Similarly, J.C. Bose's work on microwaves resulted from a careful exploration of electric wave polarization, demonstrating how pure science can reshape the world. C.V. Raman's questions about the colour of the sky and the sea led to discoveries in light scattering that transformed science. Many advances begin with questions that lack immediate answers or applications, but they form the foundation of entire industries. For example, CRISPR-based gene editing, initially driven by curiosity, now revolutionizes medicine and agriculture worldwide.

Investing in basic research is not only wise but vital for India's progress [8]. Neglecting basic research risks missing major discoveries and compromise absorption of newer technologies developed elsewhere. However, basic research in India-specific areas of importance could be made attractive by introducing attractive grants for targeted initiatives. A strong innovation system relies on solid firmament of basic research to foster discovery. Foundational research underpins product innovation, even when progress is slow or uncertain, and creates the knowledge needed for local technological advancement. According to the World Intellectual Property Organization (WIPO) 2024 Report, India now ranks sixth among the world's leading patent offices. India's rise in the global innovation index, from 81st in 2015 to 39th in 2024, shows significant progress.

Facilitating the translation of basic science into practical applications is important, but requiring direct commercial outcomes can restrict scientific creativity. Academic freedom should be given to pursue innovative projects, and the granting mechanism should be free of difficult bureaucratic processes. At least 60% of basic research should advance without immediate market demands. India needs to establish world-class basic research centres that connect research institutions, hospitals, and industry to accelerate the translation of discoveries, while preserving flexibility for foundational research. With significant funding and adherence to global standards, these centres can maximize impact and enhance India's global scientific standing. Global collaboration with diverse faculty would need to be felicitated. The government can support research funding from non-governmental sources by introducing tax credits for private sector collaborations and reinforce mission-mode programs focused on national priorities. Targeted funding, meaningful incentives, and attractive career paths are crucial for attracting and retaining top

scientific talent, as well as driving high-impact breakthroughs. Countries like China have done this very successfully and need replication in the Indian context. Policy frameworks would need to address India's specific challenges, which may differ from those in other countries. The following is a summary:

1. Promote Academic Freedom in Basic Research.
2. Establish internationally recognized centres for basic research, to facilitate international collaboration, create congenial ecosystem for sustained innovation, and ensure the effective and timely implementation of funding through responsible and responsive mechanisms.
3. Implement targeted funding mechanisms and adaptable project timelines to support diverse research needs.
4. Simplify time of approvals from regulatory agencies.
5. Fortify intellectual property protection.
6. Expand Employment Opportunities in Science through the creation of jobs in relevant sectors.
7. Create and incentivize a tax credit system to private citizens, philanthropist to support scientific research.

Rigorous ethical standards: essential for global competitiveness

India continues to face significant challenges related to research misconduct, as evidenced by a 2.5-fold increase in retractions of scientific publications since 2017 [9, 10]. Although, recently announced negative marking in the National Institutional Ranking Framework (NIRF) aims to address unethical practices, there is a need for standardized procedures to identify misconduct. Retractions must be carefully evaluated, recognizing that not all are due to fraudulent activity. For a fair assessment, an integrity officer of integrity and domain expertise, should systematically review laboratory records, computer charts, reagent logs, original files, and analyse histories after a retraction. Retractions caused by plagiarism, image manipulation, or fabricated data should result in penalties, while those due to reproducibility issues may indicate unintentional errors.

Scientists are accountable to the public, since government resources support research. Maintaining strict standards is essential to prevent resource waste and uphold public trust. Internal oversight mechanisms for research ethics should be integrated into the regular operations of scientific organizations.

A summary is given below:

1. Lay down standards for data archival and maintenance.
2. Appointment of an integrity officer from faculty members on rotational basis and with domain expertise.
3. Take steps to prevent scientific fraud through continued education and motivation.

Conclusions

This article identifies critical challenges that need to be addressed to expand and sustain the scientific enterprise in India. India's large population presents substantive challenges for its education, healthcare, and agriculture. Although these are not discussed in detail here, future national investment would need to prioritize machine learning, artificial intelligence, quantum computing, environmental sustainability, and clean energy. Advancing the biotechnology sector is also crucial for addressing emerging challenges in health and food security.

Research funding in India is often fragmented across agencies, highlighting the need for a cohesive national structure and this to some extent has been achieved by the formation of ANRF. Mechanism for integration/interdisciplinarity in its working would also be required. The institutional framework for faculty employment requires reform, especially to facilitate targeted hiring in critical research domains. Greater emphasis on interdisciplinary research and teaching is necessary to address complex scientific challenges. Maintaining research continuity is critical because laboratory operations frequently cease when faculty members retire. This interruption leads to incomplete projects and the forfeiture of prior institutional investments.

Increased private sector participation in research is essential. As of now only government funding predominates and industries tend to support only in house activities. A framework should be developed to facilitate sustained, high-risk research initiatives. Existing incentives for early-career scientists engaged in innovative research remain insufficient. The continuous formulation of progressive policies is vital. Furthermore, consistent engagement with the public is required to foster trust in scientific research.

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Science and Technology Ecosystem of India: Present State & What is Needed?

Umesh Vasudeo Waghmare

Scope

In this brief note, we focus on introspection of the present state of science and technology (S&T) ecosystem in India and suggest what could be done by Indian scientists, government and policy makers to shape its future that is globally competitive and sustainable due to its impact on S&T as well as on the Society.

Scientists and S&T: Status in society

While the parameters and their relative importance used in evaluation by the National Institutional Ranking Framework (NIRF) could be argued, their ranking in recent years consistently shows that top-ranking institutions are dominated by the Indian Institutes of Technology (IITs), Indian Institute of Science (IISc), the Institutes of Science Education and Research (IISERs), and a few universities. These, and even most of the private institutions appearing in these lists, clearly show the dominance of S&T in our educational institutions with overall high ranks. The point here is that our System (including people) favors science and engineering as educational disciplines in preference over arts, humanities, law, music, and others. This also translates to leadership of various institutions. While directors of IITs are more likely to be engineers or scientists, vice chancellors of universities too are often from S&T disciplines. This is an indicator of the lack of diversity in educational backgrounds of leadership which is not quite healthy for our educational organizations: diversity helps in promotion of critical thinking, creativity and scientific temper.

It is often an assumption that scientists are some of the best leaders and that they are intellectually equipped to solve most of the problems. It is unscientific to work on this premise, and I wish to present an example that is an important current issue — gender imbalance. It is abundantly evident that women are underrepresented in most disciplines of science

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and technology. There is no argument that this needs to change and there is need for multi-pronged effort to address it. However, members of most women in science panels or programs are primarily scientists or engineers. I believe that the role of sociologists and professionals from related disciplines is expected to be critical in tackling issues like gender balance. The bottom line is that we as scientists need to be far more open in having non-scientists (and broader society) to work with.

Lines of divide: Thinking in silos

Our (India's) educational ecosystem has been divided inherently along many lines. The division between S&T and Arts-Humanities was highlighted in the last section.

Until about a decade ago, most of the top institutions in NIRF ranking had stronger emphasis on either undergraduate education or on graduate education. This means a division between knowledge imparting (or training) and knowledge creation (research), an aspect that was highlighted in the National Education Policy 2020 (NEP 2020). For a globally competitive university, it is crucial to have seamless integration of UG education and research.

I also perceive a line of division between fundamental and applied research in many fields. In physics for example, there is often a tendency or bias of giving greater "respect" to certain types of work or topics than the others. A similar division between organismal and molecular biology is evident. We see a deepening division between basic and translational research these days, which is impacting the decisions on funding for research. This division thus involves scientists as well as policy makers, and relates to the gap between academia and industry.

Long-standing separation between medical or biological sciences and engineering or physical-chemical sciences is evident. Most of the top institutions cited above (IITs) have had no medical school or strong efforts in biology, with a few recent changes that augur well for the future. Such division compromises the wholesomeness of education. The disciplinary boundaries need to give way to more holistic interdisciplinarity in education and research, another aspect centrally highlighted in the NEP 2020.

Inadequate cooperation and suboptimal synergy among Indian researchers is at times attributed to (a) the system of rewards and recognition, (b) lack of enough funds leading to professional competition and insecurity. This results in lack of people committing to development of instruments, techniques or methods (which takes a long time often with no immediate fruit). There is a need to change this and ensure

sustained and assured funds for such endeavors that translate into long-term intellectual security of the Nation.

Trust deficit

It is often questioned what has R&D in the S&T ecosystem delivered to society or the Nation? Before I elaborate on this, I must emphasize that efforts at every institution are important and contribute to the overall growth of S&T ecosystem. It is admitted that there is a lot of scope to improve efficiency, optimal utilization of resources and strategic planning. While the outcome delivered by organizations like ISRO, DRDO, DAE (specifically BARC, IGCAR and NPCIL; some institutions are likely to be missed here) are quite readily visible, highly significant contribution of the educational (IITs, NITs, universities) and research institutions (including AI's of DST, DBT, DAE, CSIR, ICAR, ICMR) to generation of well-trained human resources has to be recognized. Large numbers of their alumni have gone on to work at other organizations in India, overseas and in industry. Acknowledging this, the government should feel absolutely certain in trusting and funding such institutions creating capacities for the future.

One often wonders why the industry in India contributes so little funds to research in S&T. There seems to be hope and drive among the policy makers in the government agencies that industry can be brought on board *overnight*. I do not believe it is likely to happen in a short time frame and government policy makers must exercise patience and thought. In UK for example, universities have a long history (some since the 12th century) and have been important force driving the industrial revolution from the inception. Hence, the industry-academia relationship there has organically grown and matured to the present state of mutual trust. In the Indian system, we may need to look for a different model of such growth given the present state of our Academia and industry, and of the ecosystem. As a first step, we must initiate a dialogue that generates confidence and creates schemes to be sustainable. The Research, Development and Innovation (RDI) scheme with a sizeable corpus created by the Government will hopefully be a stimulant to industry.

Current state: Analysis and understanding

In India, we are well below critical mass in any area of research of contemporary relevance. This is certainly linked to sub-critical funding (less than 0.7 % of GDP reduced further by GST) for research and development. India had 260 R&D researchers per million population (in 2022) and holds a rank of 39 currently in the global innovation index (GII), see Table below. While size, history, economy of a country and many

factors are quite relevant to a measure of performance like GII (taken as an example here), a few observations are noteworthy.

Table 1: *Data sourced from various sites pointed by the google search. Numbers may be slightly inconsistent in terms of the year, etc, but are surely indicative.*

Country	R&D researchers per million population [total number of researchers]	% of GDP on S&T, (GDP (T US $)), [total expenditure <T $> on S&T]	Rank in Global Innovation Index Global Innovation Index - Wikipedia	Annual S&T expenditure (M US $) per researcher
India	260 [390000]	0.67 (4.19) [0.028]	39	0.072
China	1690 [2366000]	2.56 (19.2) [0.492]	11	0.208
S Korea	9080 [454000]	4.93 (1.85) [0.091]	6	0.200
USA	4450 [1513000]	3.6 (30.5) [1.098]	3	0.726
Switzerland	6020 [54000]	3.3 (0.937) [0.031]	1	0.574
Brazil	888 [188250]	1.2 (2.13) [0.026]	50	0.138
Israel	8342 [83420]	6.3 (0.514) [0.032]	15	0.383
Singapore	6700 [40200]	1.85 (0.574) [0.011]	5	0.274

The total budget for research and development in China and Switzerland is 55 and 23 billion US dollars respectively, while the Indian S&T budget is about 2.74 billion US dollars. Populations of China and India are comparable, while that of Switzerland is more than 140 times smaller. Interestingly, more than about 80 % of the Swiss budget for R&D comes from industry. The total number of researchers (compare with Brazil), role of industry and significant funding (with well-structured ecosystem; compare with Switzerland) seem to support an ecosystem with high Innovation. Comparison with China clearly reveals that we are subcritical in the number of researchers, and even more subcritical *in per-capita* funding for research.

Despite the low spending on R&D and S&T, India is the third highest contributor to the number of papers published annually. From the data summarized here (see Table), it is very likely because of its relatively large total number of researchers. We note that USA and China, who lead in the total number of articles published annually, have 4 and 6 times the total number of researchers with much larger budget allocations. I note that the Purchasing Power Parity (PPP) may reduce these disparities a bit but may be partially compensated by the ease of living.

South Korea and India became independent at the same time, and South Korea with a population of 5.3 crore spends 25 billion US$ on R&D, about 10 times more than India in absolute terms. Strikingly, South Korea has comparable (12% more) number of researchers, and 10 times greater budget. Economics is indeed (not surprisingly) an important

factor which evidently correlates with higher GII (probably with number of high quality research publications too). It is in a sense for a similar reason that India suffers from brain drain. Large number of Indian researchers prefer working abroad for better quality of life and stronger S&T ecosystem that enables greater academic achievements.

From my experience of 25 years of working in India and a large number of collaborations, I sense that competition is more dominant a driving force than cooperation among the researchers in India. This has some roots in the fact that we have little resources per capita and consequent insecurity, and also the value system of credit and assessment that is plagued by the lines of division I presented earlier.

Concerns

Owing to the lack of organized and up-to-date data on researchers, infrastructural and human resources, and institutions, many new initiatives in the Indian S&T get introduced not relying on adequate data. While they probably have a goal of filling in the gaps in our S&T ecosystem, they do not come with additional funding and can come at the cost of existing strengths leading to creation of new gaps in longer term. For example, promotion of translational research should not lead to depletion of existing strengths in basic research. It is difficult to overemphasize the role of basic sciences ("The Usefulness of Useless Knowledge" by Abraham Flexner argues that many of history's most significant scientific and technological breakthroughs have come from research motivated purely by curiosity, not immediate practical application), which is key to long-term sustenance of any Nation.

There are two adverse effects of the divisions we have in our S&T system along various lines: (a) researchers do not quite work together (beyond sharing techniques; mega-projects are sort of exceptions due to sustained and secured funding) with a goal to solve challenging problems, and (b) there is little *collective thinking* in developing novel ideas locally. On a lighter note, people say that a researcher does not know of a similar kind of research conducted down the corridor. There is need to have excellent conferences in each field, that would balance the quality and large numbers of participants. With rapidly growing interactions over social and other media, which favor shallow and populous interactions and hence collective stupidity, I caution that we must avoid the emerging mental laziness (short-cuts to supporting each other) and act to promote in-depth collective and critical thinking.

Since S&T ecosystem in India is subcritical in both funding and number of researchers, optimal utilization of funds and human resources is critical. While the latter may be achieved by promoting collective

thinking, the former needs *autonomy* which must be balanced with *accountability*. Due to lack of this balance built in the system, autonomy of most government funded research labs is on a downward sliding path. Autonomy through decentralized control on utilization of funds at all levels and intrinsic structural accountability possibly with digitization would help. There is a need for a financial model for a given (type of) institution and its proper understanding by its researchers. This should make each researcher appreciate the responsibility and entitlements of her/his position and achieve self-driven sustainability.

Issue of ease of doing science (from release of funds, procurement, restrictions on utilization to reviews) is an important one, on which a document was prepared by the Indian Academy of Sciences, Bangalore (2024) and shared with the relevant ministries.

How academies and others may help

Hypothesizing that the government offers to double the S&T budget in the next five years, an important question is if we are ready with a strategic plan to make this transition. Perhaps, not. A detailed meticulous plan and recommendations for practical implementation are much needed, involving most stakeholders. I suggest below some actionable items with this goal.

Development of Multi-scale financial models that assist in achieving sustainability of our institutions and the maintenance of their infrastructure. This will necessarily involve cooperative efforts between scientists and experts in finance and management.

Strengthening of our Universities. Justification: (a) we are below critical mass, (b) many existing institutions having limited capacity for growth or for doubling their size in a short time may not be healthy, (c) universities have huge landmass and potential to grow (in size as well as in the direction of Arts and Humanities, etc). Caution that must be exercised: (a) the management and recruitment of staff (leadership included) at the universities need to be reformulated with autonomy and accountability, (b) one may consider the model of land grant university in the USA (Morrill Act of 1862 and 1890), updated to suit the present Indian situation. Much broader set of recommendations in a document prepared by the Indian Academy of Sciences, Bangalore (2024) may be an excellent starting point. Recently launched PM Professorship (2025) by the Anusandhan National Research Foundation is a welcome step in this context.

Recommendation for the **phase wise increase in the government budget** (say from 0.7 to 1.5 % of GDP). A clear plan for this major transition from the state of low funding to that with high funding over

the period of 5-10 years. Detailed plan(s) should be prepared highlighting how existing areas of strength will grow and how the gap areas will be filled in.

It is desirable to develop an **Indian S&T Cloud Database** that maps the data (geography, other attributes) on expertise and key research areas of scientists, engineers, industry experts, colleges, research instrumentation, national facilities within India. This will also include information on the networks of collaborations, bank of research problems (of interest to academia and industry), bank of job openings. Naturally, such a database will be dynamic, and updated interactively. The goal of such a resource is to promote cooperation and collective thinking among Indian researchers, and possibly benefit from the advances in AI-ML, particularly generative AI.

Summary

Success of the Science and Technology ecosystem, which is important to growth of a country, cannot be measured with only the immediate or short-term revenues and benefits it brings. Being subcritical in the strength of researchers is the crucial fundamental issue of Indian S&T. Significant increase in the national expenditure on R&D in S&T, and careful phase-wise and well-organized data-based strategic planning for its optimal utilization are much needed. Strengthening universities and engagement of industry within the S&T ecosystem are highly desirable but we will need an indigenous socio-financial model to achieve them. Balanced autonomy and accountability at various levels, and openness to diversity (with focus on universities in particular) will strengthen India's S&T ecosystem enabling innovation, inclusive and sustainable growth.

Note: Views expressed here are personal, and do not represent any institution. The author acknowledges stimulating discussions with Professor Subi J. George and edits by Professor A.K. Singhvi.

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Scientific Misconduct in India and Some Preventive Measures

Partha P. Majumder

Scope

Scientific progress thrives on trust, rigor, and reproducibility. It is the cornerstone of technological development, health innovation, and social advancement. However, this delicate foundation is vulnerable to collapse when scientific misconduct infiltrates the research process. Defined broadly as fabrication, falsification, plagiarism (FFP), and other forms of unethical behaviour, scientific misconduct undermines the validity of research and erodes public trust.

India, with its rapidly expanding research ecosystem and global ambitions in science and technology, faces serious challenges in maintaining research integrity. Increasing reports of misconduct in Indian academia – including plagiarism, ghost authorship, data manipulation, publication octopuses and publication in predatory journals — highlight systemic flaws that need urgent redress. This essay explores the causes and manifestations of scientific misconduct in Indian institutions and outlines practical strategies for prevention and governance, drawing from global best practices.

Prevalence in India: a growing concern

According to Nature Index 2024, India's research output now ranks 9th globally (https://x.com/NatureIndex/status/1802960997885636962?lang=en). There has been a significant transformation of higher education in India in recent years. There is now a great emphasis on research output and competitive ranking. As a result of these emphases, while the number of research publications from India was 26, 664 in 2001, the number stood at 3,70,595 in 2024 (https://www.policycircle.org/opinion/research-publications-india/); a 14-fold (or, over 1200%) increase in about 25 years. This deepening of India's footprint on science is certainly welcome. However, associated with this huge increase is the

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sad tale of scientific misconduct. The retraction rate of publications has increased over the years, and India now ranks third in the number of retracted papers. The two countries with rate of retraction higher than India are China and the USA (https://postpub.net/). Of course, published papers may have to be retracted for a variety of reasons, including honest mistakes. However, even though India ranks below China and the USA in the total number of retractions, it actually ranks above these two countries in the percentage of papers with "serious alterations" (48%, compared to China's 34% and USA's 38%). An incentive for acts of scientific misconduct is that increased number of publications for an academic is that (s)he is rewarded by promotions and awards. For an institution to encourage its faculty members to increase the number of publications — even if by acts of scientific misconduct — is to enhance its rank on the National Institutional Ranking Framework (NIRF). On September 8, 2025, following strong criticism from academia and the media, the newspaper "The Hindu" reported that "Many research retractions stem from institutions attempting to climb the rankings through fraudulent or unethical practices. Anil Sahasrabudhe, Chairperson of the National Board of Accreditation (NBA), said that the NIRF would introduce penalisation for 'research retractions' starting this year and continue it in the coming academic years." This is certainly a welcome step.

Steps that may be taken

Policies and definitions to be clearly defined

1. Among researchers, there is enormous variability in comprehending what constitutes 'scientific misconduct'. It is, therefore, essential that adoption and publicity of clear definitions of scientific components that constitute scientific misconduct — including, plagiarism, fabrication, falsification, guest authorship, duplicate submission, violation of ethical norms in research involving humans and animals — be done.
2. Indian National Science Academy (INSA) may play a lead role in defining a National Framework that aligns the existing guidelines formulated by ICMR, DST, DBT, UGC, CSIR, ICAR and similar national bodies.

Create cells for vigilance and protection

1. Every institution needs to be vigilant to prevent their members from indulging in scientific misconduct. Just as it is mandatory for all institutions to constitute an Institutional Ethics Committee (IEC), a Scientific Misconduct Cell (SMC) may be created in every institution. Each SMC must encourage reporting of scientific misconduct.

2. Currently, people hesitate to report misconduct of others because most often there is no protection for a whistleblower. Concurrently with the formation of an SMC, a Whistleblower Protection Cell must also be constituted.

Training and oversight

1. Training courses for PhD students and post-docs on research ethics and research integrity must be made mandatory in all academic institutions. Refresher programmes on these topics must be held periodically, which should also be attended by faculty members and other research instructors. Scientific members of institutions who provide such training must themselves be role models for ethical behaviour.
2. An Oversight Committee may be constituted in each institution so that integrity checks are done internally before submission of major projects for funding and manuscripts for publication. Reports of tools to check plagiarism must be made mandatory along with any document submitted to the Oversight Committee. For reviewing a document, the Oversight Committee must insist on a declaration from the submitter about the role of each author listed on the document. Wherever relevant, the Oversight Committee must insist on access of the raw data for internal review.
3. When an Oversight Cell has reasons to believe that someone has indulged in scientific misconduct, an investigation should be carried out in such a way that it is unbiased, fair and time-bound. If misconduct is proven, appropriate authorities must penalise those who have participated in the misconduct. One possible penalty may be to not consider the person(s) for promotion for a period of time.

Role of Science Academies

Science Academies, such as INSA, IASc, and other academies, must actively promote ethical behaviour of those engaged in science. The variety of ways in which ethics promotion can be done cannot be exhaustively listed. The most effective way is to organize training in scientific ethics and appropriate conduct. This must be done not as a ritual, but as a focal activity of every science academy. The academies must also actively send that signal to the entire scientific community that there is zero tolerance of scientific misconduct. No nominee with any reasonable evidence of misconduct should be admitted to the Fellowship of any science academy and that the selection to their fellowship should conform to the highest standards of ethics. Scientists admitted to the Fellowship but subsequently

found to have indulged in misconduct either before or after admission should be suitably admonished and possibly delisted, even if for a fixed period of time.

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He has immensely contributed to capacity-building in human and statistical genetics in India. He has published a textbook in 2023 titled *Statistical Methods in Human Genetics,* Springer.

He has founded the *National Institute of Biomedical Genomics*, an institution of the Government of India. Earlier, he had established, on behalf of the Indian Statistical Institute and in collaboration with The Chatterjee Group, the *Centre for Population Genetics*.

He is an elected Fellow of all the three national science academies of India, The World Academy of Sciences (TWAS) and the International Statistical Institute. He has served as the President of the Indian Academy of Sciences (2019-2021) and of the West Bengal Academy of Science & Technology (2016-2020). He serves on governing boards or other similar committees of many international organizations, including the Human Genome Organization, the Human Cell Atlas consortium and the World Health Organization.

He has received many awards and honours, including the G.N. Ramachandran Gold Medal (2021) of the Government of India; Barclay Memorial Medal (2020) of The Asiatic Society; Golden Jubilee Commemoration Medal (2018) of the Indian National Science Academy; Centenary Medal for Excellence (2014), School of Tropical Medicine, Kolkata; TWAS Prize in Biology (2009) of The World Academy of Sciences, Trieste; New Millennium Science Gold Medal (2000) of the Govt. of India.

Higher Education: The Crisis of Leadership in Public Institutions

P. Balaram

Scope

The declining standards in public universities across the country may be traced to a crisis of leadership, compounded by growing politicisation of appointments. The importance of visionary leaders is illustrated with three examples from the history of India's universities. In the pre-independence era, Ashutosh Mukherjee transformed Calcutta University, ushering in a renaissance, which has proved impossible to replicate. In the post-independence era, A. Lakshmanaswami Mudaliar at Madras and Maurice Gwyer at Delhi demonstrated that enlightened leadership can be transformative for institutions.

Introduction

In revisiting the much-discussed area of higher education reform in India it is inevitable to lament the all too visible signs of decay in publicly funded colleges and universities. The steady decline over the last fifty years has been manifestly evident. In the area of science, which undoubtedly concerns the Indian National Science Academy (INSA), the rise of national laboratories and Institutes of Science Education and Research (IISERs), along with the Indian Institutes of Technology (IITs) has further accelerated the decline of the University system. The rapid mushrooming of private universities and the more recent discussions on entry of foreign universities will undoubtedly further speed the decline of the public higher education system. The Editors of this volume have clearly instructed authors to be prescriptive: "*We often talk about what is not good in the Scientific/Education ecosystem, and this will be the*

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time ripe to record as to what could and should be done now, to secure the future, that nurtures creativity, critical thinking and a merit based, enabling system." Having observed decades of discussion on Higher Education and Research in India it is hard not to have a feeling of *déjà vu* when confronted with a New Education Policy in 2020 (NEP-2020). Many years in the making, one hoped that the long gestation period for NEP-2020 would result in a road map with a clear implementation strategy and plans for comprehensive and purposeful reform. Five years down the line, the reform of the higher education regulatory system proposed in NEP-2020 has all but been forgotten, signalling, once again, that policy proposals announced with fanfare can easily be derailed by obstacles and a lack of commitment in its implementation. In a vast and unevenly developed country like India, publicly funded institutions, particularly state and central universities, remain the only accessible avenue for higher education, for large segments of the population. Yet, state universities are the chronically underfunded, most impoverished institutions in the landscape of higher education. Even more importantly, their governance has touched new lows with constant Centre-State bickering on the appointment of Vice Chancellors and rampant political interference. In its report on education (1964-66), the Kothari Commission emphasised the importance of the Vice Chancellor, noting that the person must "*embody the spirit of academic freedom and the principles of good management*" and stand for the "*commitment of the university to scholarship*". Nearly two decades earlier, the University Education Commission (1948-49) had suggested that the university must learn how to choose its Vice Chancellor wisely, noting that to deprive it of this duty would be a "*counsel of despair*". These observations have never influenced any Government.

The present crisis of leadership, coupled with severe financial and administrative constraints, has resulted in a depletion of faculty strength even in traditionally strong academic departments, across the country. In many places, guest and contract faculty, hastily recruited at the start of the semester and promptly terminated afterwards, is the norm. This glaring neglect of the faculty in our state universities, together with the declining strength of teachers in institutions running post-graduate courses, has resulted in the near extinction of many academic disciplines. Once proud and vibrant departments now stand as deserted relics of another age. Sadly, this decline coincides with the rise of private institutions, a rapidly expanding economy and an increasing demand for access to higher education. In attempting a revival of several old universities, steeped in tradition, one can ask what factors contributed to their early successes, albeit for a few decades, before the decline set in. Understanding both the causes for success and the reasons for decline may lay the foundations for

the reforms of the future. In reflecting on the history of some examples of Indian Universities in recent times, I can justifiably take heart from the oft stated dictum, attributed to George Santayana, that "*those who fail to learn the lessons of history are doomed to repeat it.*"

Mahendra Lal Sircar and Jamsetji Tata

Any consideration of higher education in India today does not need to go back further in time than 1857. Harking back to the legendary glories of Nalanda and Takshashila, while psychologically comforting, may not be helpful in charting a course for our universities today. 1857, a year etched in Indian history, is when the Universities at Bombay (now Mumbai), Calcutta (now Kolkata) and Madras (now Chennai) were born, at a time when the East India Company's role faded and the British colonisation of the sub-continent gathered pace. Their mandate, a direct offshoot of Macaulay's infamous minute of 1835 on education, was to train a new class of "educated" Indians to serve the growing needs of the British Empire in India. The mid-19th century was also a time when the tumultuous advance of the Industrial Revolution, based on the rapid development of the physical and natural sciences in Europe, was transforming centres of learning in England, Germany, France and Italy. Natural philosophers were slowly transforming into modern scientists and academicians.

In the second half of the 19th century and in the context of accelerated pace of scientific and technological advances in Europe, the recognition that scientific research and higher education were important for India's future was not due to the British government of the day. Indeed, it was the vision of two Indians, Mahendra Lal Sircar and Jamsetji Tata, who thought far ahead of their times and dreamt of scientific research in contemporary India. The former founded the Indian Association for the Cultivation of Science (IACS), Kolkata in 1876, while the latter created the blueprint for the formation of the Indian Institute of Science (IISc), Bangalore, in 1896. IISc, born in 1909, had a long gestation period, necessitated by a tangled relationship between the House of Tatas, the British Government and the Kingdom of Mysore. IACS, conceived for the advancement of science by public engagement, burst dramatically on the scene in the 1920s, with C.V. Raman's now legendary work. IISc had a less dramatic beginning, but in its first three decades built the firm foundations for a large number of science and engineering departments, whose alumni went on to catalyse the growth of these disciplines in post-Independence India. At the beginning of the 20th century, the Universities were not centres of research and knowledge creation. Rather, they were examination and certifying bodies serving a growing number of constituent colleges. The Research University was unknown in India at that time. The original document (1900) for the

creation of IISc is presciently titled '*An Indian University of Research*', implicitly recognized the intimate connection between teaching and research. With this preliminary historical background, we can return to the Universities set up in 1857.

Calcutta university and the Bengal renaissance

Change was in the air in the first decade of the 20th century. Bengal, the first foothold for the East India Company in India, was a fertile ground for the spread of English education. Over 200 years ago, the precursor to the Presidency College had been established and in 1855 the college acquired its new name, now immortal in the history of higher education in India. Presidency College was to go on to become the centre of the scientific renaissance over half a century later, a striking example of a constituent college becoming the intellectual centre of the University. In 1906, Ashutosh Mukherjee (1864-1924), trained in mathematics and law, a jurist of distinction, was appointed the Vice Chancellor of Calcutta University. He held this position from 1906-1914 and again from 1921-23 and was associated with academic bodies of the University for many decades. If there is one man who can be credited with catalysing the Bengal renaissance, an intellectual revival that sparked the flowering of modern science in India, it is Ashutosh Mukherjee. Together with his great contemporaries, Prafulla Chandra Ray and Jagadis Chandra Bose, he created an environment which supported and inspired, a galaxy of scientists and scholars. C.V. Raman, Meghnad Saha and Satyendranath Bose, amongst them, went on to transform the intellectual landscape of pre-Independence India. In her tribute to Ashutosh Mukherjee, Santishree Pandit concludes: "His leadership as Vice Chancellor of Calcutta University transformed the university from a degree-granting office to serve the colonial master into a global research university, allowing platforms for Indians to display their intellectual capital." (*The Sunday Guardian* September 7, 2025).

For six decades, until the mid-1960s, Calcutta University was an academic institution which nurtured generations of students, in an atmosphere that stimulated the intellect. In the last six decades, the University has struggled, in an increasingly vitiated intellectual atmosphere, where political ideology trumps independence of thought, an example of the growing malaise that has affected the sphere of higher education and research in India. Ashutosh Mukherjee was also the first President of the Indian Science Congress Association (ISCA), in the meeting held in 1914. ISCA, of course, is the body that midwifed the formation of INSA two decades later. It is ironic that as INSA prepares

to address the decline of the higher education system, in marking its 90th anniversary, ISCA has faded into obscurity.

Madras university's golden age

Moving south, the University of Madras provides a second example of the role of leadership in setting the tradition of a great university. A. Lakshmanaswami Mudaliar (1887-1974), a physician, was appointed Vice Chancellor in 1942, the year that the Quit India movement was launched signalling the inevitability of the end of British rule in India. Mudaliar remained as the head of the university until 1969, an unprecedented tenure of 27 years. The University had two constituent colleges, Presidency College (1840) and Madras Christian College (1837), which had been established much before the University. While undergraduate science education was not far behind the rapidly moving front of Western science, the University served primarily as an affiliating and overseeing institution, much like its counterpart in London. Knowledge creation was yet to appear on the agenda. Knowledge dissemination did far better. Presidency College Madras boasts of both C.V. Raman and Subrahmanyam Chandrasekhar amongst its alumni. Mudaliar recognised that the University must become a centre of research. It was under his stewardship, on the advice of C.V. Raman that the Physics department was born in 1951, with G.N. Ramachandran, then only 29, as its head. For nearly two decades thereafter, Madras was recognised as one of the world's leading centres in the rapidly growing field of molecular biophysics, now transformed into structural biology. In the decades of the 1950s and 1960s, chemistry, biology and many other academic disciplines flourished not only in the University, but also in constituent colleges. Over two decades after independence, in the 1970s, the decline set in. The last half a century has seen as many as 16 Vice Chancellors struggling to stem the tide. The examples of Madras and Kolkata exemplify the fate of institutions that established strong research centres before and after Independence. Their declining periods coincide with the changing political and social landscape of India. They also coincide with the gradual fading of a generation of Indian academicians, who grew to maturity in the heady days of the freedom struggle. They were driven by optimism and hope that higher education would nurture a new generation of their fellow citizens and drive the growth of India into a resilient and prosperous country, competitive with the advanced countries in all of its academic endeavours.

There is a third example which is instructive, the University of Delhi. In many ways Delhi was the last of India's major cities to acquire its own University. Delhi, of course, stands apart from Calcutta, Madras and

Bombay, which became the centres of British power in the 19th century. As the Mughals declined and eventually fell, Delhi ceded its central place to the others, each of which became the seats of the three large presidencies, through which the British imposed their influence. Kolkata was the seat of the central government. Unsurprisingly, it also grew into the centre of intellectual activity as the century drew to a close.

The Universities of Punjab (1882) in Lahore and Allahabad (1887), were followed by another Indian initiative, Pandit Madan Mohan Malaviya's creation of the Banaras Hindu University in 1916, which also marked the establishment of the University of Mysore. The Grand Durbar in 1911, was the turning point of Delhi's fortunes in the 20th century. In addition to crowning himself as the Emperor of India, King George V also announced the transfer of the imperial capital to Delhi. Not long after, the idea of a university in the capital city was mooted in 1911-12. The gestation period from conception to birth was a decade. The University came into existence in 1921, with two constituent colleges, St. Stephens (1882) and Hindu College (1899). A wonderfully readable essay, by the scholarly Delhi University historian, Aparna Basu (1931-2018) traces the early years [1]. Between 1921 and 1938, the University remained a largely administrative and certifying body with academic activity restricted to its constituent colleges. The transformation began in 1938 with the appointment of Maurice Gwyer (1878-1952), a British jurist who had a long tenure as Vice Chancellor, 1938-1950. The University's condition, seventeen years after its inception is best reflected in his description of the administrative offices located in the Viceregal Lodge: '*Walls were stained with damp and plaster was coming off them; the roofs and ceilings were decayed. The library was a disgrace*' (Basu, p 419). Gwyer had a vision of the University he sought to transform: '*India stands on the threshold of a new era which will make Delhi again one of the great cities of the world; and it would be a lamentable thing if the New India and the Old Delhi were content with a University which did not reflect in the sphere of intellect and culture the illimitable destiny of the Indian people' (Basu, p. 422).*

Gwyer recognised that the quality of a university is entirely dependent on the quality of its faculty. Like Ashutosh Mukherjee in Calcutta before him and his contemporary Lakshmanaswami Mudaliar in Madras, Maurice Gwyer devoted much of his time to attracting to Delhi the most promising scholars of that time. His ability to spot talent must have been exceptional as the list, of the people he encouraged and brought to the University in the 1940s, shows: D.S. Kothari had joined in 1934, but science teaching was restricted to undergraduates. Gwyer entrusted him with the larger responsibilities of post-graduate teaching and research

resulting in the growth of physics and the science faculty; those who came in the 1940s included the economists B.N. Ganguli and V.K.R.V. Rao, the botanist P. Maheshwari and the organic chemist T.R. Seshadri. Others followed soon after, making Delhi University a great centre of scholarship in the 1950s and 1960s. Despite its status as a centrally funded institution in the national capital, the following decades saw a perceptible decline, gathering pace in recent years.

Wishing for the impossible

All three examples that I have considered here emphasise the importance of enlightened leadership and its stability over long periods of time. Today, vice chancellors, who are well-intentioned, face a daunting task in confronting the challenges that the environment, social and political, imposes on our universities. If a beginning is to be made in attempting the resurrection of at least some of our universities, careful choices of leaders and longer tenures may well be a starting point. At present, the process of selection of institutional heads is often mired in endless controversies in States, where ruling dispensations differ from those at the Centre, often requiring judicial intervention. This is clearly a sign that political parties of all persuasions have a deep interest in the appointments of Vice Chancellors. There is little doubt that none of the three examples that I have cited would have passed muster today.

New models of governance structures are clearly needed today to insulate universities from direct political influence. The thorough revamp of the higher education regulatory system, envisaged in the NEP-2020, is long overdue. The obsession with NIRF rankings has spread like a malignant virus with no vaccine in sight. The excessive use of numerical parameters, in attempting algorithmic evaluation of both faculty and their institutions, has contributed to the deteriorating academic state of our colleges and universities. Starved of financial resources, hamstrung by bureaucratic and political interference and devoid of strong, enlightened leadership, it is hardly surprising that our universities appear to be in a state of constant crisis.

Is there a silver lining visible in this dark cloud? Alexander Pope's immortal line, "*Hope springs eternal in the human breast*", reminds me that there must be light at the end of the tunnel. Eternal optimists, surveying the higher education scene in India and wishing for a major transformation, may well take heart from Lewis Carroll's White Queen: "*Why, sometimes I've believed as many as six impossible things before breakfast.*"

What is the ideal of a university that we all seek? I can do no better than to return to Ashutosh Mukherjee, who unveiled his vision for Calcutta University at the Convocation in 1907:

"*This will be a centre of learning and the expansion of the frontiers of knowledge. This is precisely the true ideal of the university.*"

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He was the Editor of *Current Science* from 1995 to 2013, during which he authored over 300 editorials on diverse subjects related to science and scientists.

He is the recipient of several awards and honours, including Padma Shri (2002), Padma Bhushan (2014) and the R. Bruce Merrifield Award 2021 of the American Peptide Society and the Ernesto Scoffone Prize of the Italian Peptide Society 2024.

History and Growth of Agriculture, Medical Sciences, STEM and Education

D. Balasubramanian[1] and A.K. Singhvi[2,3]

Scope

This overview chronicles the growth of Indian Scientific enterprise and shows how the initiatives in the 1950's and 1960's have helped the nation in critical areas of agriculture, health care and translational research. The green revolution of the sixties transformed India from a food-deficient, drought-stricken, starving nation to a net exporter of food grains. Likewise, the success story of India in eradicating many diseases like polio, smallpox, cholera and many others are unparalleled, and today India exports critical vaccines, saving millions of lives in the Global South. It is noteworthy that many of these vaccination initiatives have been led by women scientists. India's progress in data sciences and statistics is well known. We end with a few thoughts on the possible future trajectory to sustain the growth of Indian Science and the scientific temper, as envisioned in the constitution which envisions development of scientific temper, humanism and the spirit of inquiry and reform as fundamental duties, and its constituents.

Food and health

As we celebrate 90 years of the Indian National Science Academy (INSA), with the objective of promoting science in India and harnessing scientific knowledge for the cause of humanity and national welfare, let us look back at how India has grown from a ship-to-mouth economy (importing 5.6 million tons of foodgrains to feed 357 million people in 1950) to one which has produced about 150 million tons of rice in 2024 and exported 18 million tons. And, we produced 105 million tons of wheat in 2024 and exported about 10% of it, using the rest for internal

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consumption. Likewise, we produced 25.4 million bales of cotton in 2023-24, utilised much of it for use within the country, placing us second to China. This dramatic reversal became possible by the efforts of agricultural scientists, led by Dr. M.S. Swaminathan, FNA, for enhancing the productivity and production of wheat and rice crops during the 1960-70 period, and the productivity and export of cotton today. Presently India produces and exports about 9 million tons of the much demanded 'Basmati Rice'. And, scientists from the National Agricultural Research Institute (NARI) have used the most recent genome editing method (CRSPAR-Cas 9 technique) to improve and enhance the production of rice which is drought and salt-tolerant.

Turning to health, while smallpox killed over a million Indians in 1950, the number today is negligible, thanks to the number of doctors and vaccinations. Today, several companies in India manufacture vaccines for BCG, COVID, Shingles and other infections. Earlier, India was importing drugs but now our drug companies not only manufacture drugs but also export them to about 200 countries, notably to USA for $28 billion, and to the UK for about $11 billion. Thus, the range of medical care over the years, and the fact that these are of a global standards, is something we can be proud of. India's export of drugs last year was $28 billion, and to USA alone, it was close to $8.8 billion. Turning to doctors and pharmacists, there are 13 lakh doctors in India today (of which 10% are lady doctors) who cater to the 146-crore population. Back in 1947, the population was 34 crores and there were only 48000 doctors with the alarming ratio of 1 to 6300 people. The plan by the Health Ministry is to increase more medical colleges in the coming years to achieve the doctor: patient ratio to 1 per 1000. Today, we have about 3,000 drug companies and about 11,500 manufacturing units. These companies range in size and scope, from small biotech firms to large, multinational corporations, contributing significantly to the Indian economy and in the global pharmaceutical market. It is also heartening to know that these days, several government hospitals and private and non-profit foundations offer free or highly subsidised medical care to the needy. Thus, the range of medical care over the years, and the fact that these are of global standards, is something we can be proud of.

Gender balance and translational research

While most academies in India elect women as Fellows, it is INSA alone that has had a woman scientist as President: the biologist Professor Chandrima Shaha (during 2020-22), although the lady scientist, Late Dr. Manju Sharma, was the President of the National Academy of Sciences, India (NASI) in 1995-1996.

There are other women scientists, clinicians and technologists, who too are Fellows of some of our academies. Many of whom are involved in the application of science termed as 'Translational Research,' which is also called 'Lab to Land' or 'Bench to Bed side' and vice versa. Kiran Majumdar Shaw, FNA, the chairperson of the biotechnology firm 'Biocon', has been offering drugs and vaccines free of charge to the poor in India and Africa. Late Dr Indira Nath, FNA, had focused on leprosy and ways to reduce its burden on patients and people. She has been the only Indian scientist who has received the l 'Oreal UNESCO Award for lady scientists from India. Mrs. Suchitra Ella, co-chair of the biotechnology company Bharat Biotech, had been offering vaccines against Covid-19, and meningitis to needy poor people. Mrs. Anu Acharya of Hyderabad has a company called "Map my Genome" which offers genome matching for marriageable couple, calling it 'Genome Patri'!

Mathematics and statistics

Srinivasa Ramanujan Aiyangar (22 December 1887–26 April 1920) was an Indian mathematician. He is widely regarded as one of the greatest mathematicians who made substantial contributions to mathematical analysis. While he was a 'pure' mathematician, other mathematicians who came after him used their mathematical analysis for solving practical problems relevant to society, or 'translational mathematicians'. P.C. Mahalonobis, FNA, established the Indian Statistical Institute (ISI), which put together the National Sample Survey (NSS) for data collection, population statistics, economic conditions and the random sampling model for large scale surveys to measure crop yields, industrialization and help India's Second Five-Year Plan to promote industrialization. In recognition of his achievements, the Government of India celebrates June 29th as the National Statistics Day. Another outstanding Indian mathematician was late Professor C.R. Rao, FNA, who collected data on the population of India, which helped in carrying out the Census of India, and the number of voters across India in various states and the whole country.

Archives

INSA is unique among all the other academies in India, for having initiated the National Commission for the History of Science and its Research Council. Some of its archival materials include the writings of the astronomer Aryabhata (6th century CE) and the physician/surgeon Sushruta (6th BCE). Ancient India also developed methods to make glass, and using it, metallurgy, astronomy, ecology and forestry, art and architecture. This archive, called "The History of Science Programme", involves the collection of source material, its compilation, documentation, translation, and critical evaluation. This effort has been the major activity of

the History of Science Program, which also includes writing monographs, organizing discussion meetings and publishing the quarterly journal–the *Indian Journal of History of Science (IJHS)*. This Program is managed and organized under the guidance of experts, and the submitted article from prospective authors published after peer review. Grants are given to the accepted papers when requested.

Tuning the educational and social science system for further growth: What should India be tomorrow?

With the advances that we have made so far, we need to think about what could and should be done to ensure that every high school, college, postgraduate and doctoral degree student of today becomes a leader of India tomorrow. To assist him/her in this, let every student spend a month of his/her vacation time when he/she gets to interact with people in everyday life, such as villagers, farmers, daily wage workers, self-help groups, businessmen, doctors and local government officials, in order to gain appreciation of the needs and aspirations of those in the suburban society. At the next level, the student may spend a few weeks working with hospitals and medical centres, non-profit foundations and companies serving the society we live in. This helps prepare the student to become a Translational Researcher.

These initiatives, when achieved, will make educational centres of India of tomorrow comparable to the better ones elsewhere, and attract students from other countries to come to study here. In fact, India should strive to be a destination for education and research for the students of the Global South. This will not only enrich them but also enrich us by bringing talented minds to India, and will be a great example, and serve as models of the use of science for diplomacy. The academies can play a role in this endeavour. The Humboldt Foundation Fellowship and the Fulbright Fellowship are great examples, and such models need to be replicated with a large number of scholars visiting India. For in-field and onsite exposures of students and integration of students from elsewhere will prepare our students with a more secure system that will enable our students a secure future that nurtures creativity, critical thinking and a merit-based enabling system.

What do the ‘Ivy League’ and ‘Seven Sisters’ colleges do in the US, which attract students from India? They hold monthly seminars by inviting experts from various fields, encouraging students to dive deeper into the fields by working with experts during semester-breaks. These enrich them with a wider and diverse range of perspectives, and make them better scientists, doctors, engineers and entrepreneurs of tomorrow. If we adopt such a system in Indian universities, technology, medical, agricultural and economic institutions (IITs, institutes of CSIR, DBT,

ICMR, ICAR, ISRO, etc), there is every reason for India to become a viable and attractive destination across the world, attracting students, scholars and entrepreneurs from elsewhere. With the start-up facilities that some institutions offer, many scientists in India should be encouraged to start companies which manufacture knowledge-based products for sale and export. Thus, while Indians have been moving to 'Silicon Valley' and starting multi-million-dollar companies, we can expect to have scientists and engineers in India itself to start companies in our 'Genome Valley', Hyderabad and elsewhere in the country. The academies have a role to play in realizing this by assuming their responsibility in taking India forward.

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Modern Scientific Thinking Needs Politics of Inclusion

Sunita Narain

Scope

Almost a century is more than a lifetime. This is what we are marking when we celebrate the 90th year of the Indian National Science Academy (INSA). This ageing matters, not only because it provides us the wisdom of the venerable many who chartered new territories but because it gives us the imagination and the strength to innovate as the world around us changes. In our world today, it is a time of reflection; it is also a time of churning and a time when we are at the cusp of the age of Artificial Intelligence (AI), which promises to alter just about everything we know of knowledge and doing. The opportunities are enormous. But it will require a change in the way we do things; in the way we construct our questions of science and in our method of enquiry and investigation. We need to be nimble; to be relevant and for our science to be path breaking in the matters of today and tomorrow. This is what I want to discuss in my paper. What are the challenges for science in the age of climate change? Why science and scientists will have to connect dots between the everyday and the laboratory. Why this matters and what it will take to build this scientific temper for a new tomorrow. This is the imperative of modern scientific thinking – the need to make the connections between science and society, and between science and politics.

Climate change: the imperative of connections

This was in early 1990s — my colleague Anil Agarwal had been called by a rather harried chief minister, who had been directed by the then environment minister to ask his people to stop eating rice or keeping animals. This, because, it had been revealed by the research from the

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very respected Washington-based think tank, World Resources Institute (WRI) that this activity, added to greenhouse gas emissions, and that countries like India were equally responsible for the stock of emissions in the atmosphere [1]. This remembers was 1991, when climate change was not even on our agenda.

Anil and I had little knowledge of the science or the politics of climate change. We went into the meeting only knowing that in our experience – we had then spent the last few years traversing across Indian villages to understand what led to deforestation and how we could grow trees – was that the poor with their subsistence use of resources, however, intense, were rarely responsible for the scale of devastation we could see in the world.

As we researched the issue we learnt of the science of sinks, which would sequester carbon dioxide emissions; we understood the maths of subtracting what countries emitted from different sources and what the national and global sinks — from oceans, soils to forests — would remove. We understood that the sum of the gross emissions verses the net emissions of each country came down to the politics of appropriation. Who would have the right to the global sinks? Should it be divided based on the biggest polluter (as was the maths used by WRI) or should it be divided based on the right of every individual of the world to the global commons (as we did and then published in our 1991 volume: Global warming in an unequal world, a case of environmental colonialism [2]). It was science and it was politics.

The 'scientific' methodology used by WRI to compute the responsibility of each nation favoured the polluter. Under the WRI methodology, each nation was assigned a share of the Earth's ecological sink proportional to the countries contribution to global emissions.

WRI had estimated that the world produced 31,000 million tonnes of carbon dioxide (CO_2) and 255 million tonnes of methane every year. It then estimated that the sinks of the Earth, naturally assimilated 17,500 million tonnes of CO_2 and 212 million tonnes of methane annually. On this basis, it then computed a "net" emission of each nation, by allocating a share of the sinks to each nation, based on its gross emissions contribution. In this way, if a country had a higher gross pollution, it also got a higher share of the sinks. Its 'net' contribution got reduced.

We argued that there were two main types of 'sinks' where CO_2 is reabsorbed by the biosphere: the oceans and terrestrial sinks. While terrestrial sinks, such as forests and grasslands, may be considered national property, oceanic sinks belong to humankind. They must be regarded as common global property.

We apportioned the sinks on the basis of a country's share in the world's population, arguing that each individual in the world had equal entitlement to the global commons. This allocation, based on individual rights to the Earth's natural cleansing capacity, changed the computation of the nation's responsibility drastically. For instance, under the WRI methodology, the US contributed 17% of the net emissions of the world, while our methodology computed that it actually contributed roughly 27.4% of the net annual emissions. Similarly, the contribution of China decreased from the WRI estimated 6.4% of the net annual emissions to 0.57% and India from 3.9% to just 0.013% of the net annual emissions.

We put forward the following submission:

One, the world needed to differentiate between the emissions of the poor — from subsistence paddy or animals — and that of the rich — from, say, cars. Survival emissions were not, could not be equivalent to luxury emissions. We also recalculated the methodologies for estimating the methane from cattle. This was then further developed by Indian scientists.

Two, it was clear that managing a global common meant cooperation between countries. As a stray cattle or goat is likely to chew up saplings in the forest, any country could blow up the agreement if it emitted beyond what the atmosphere could absorb. Cooperation was only possible — and this is where our forests experience came in handy — if benefits were distributed equally. We then developed the concept of per capita entitlements — each nation's share of the atmosphere — and used the property rights of entitlement to set up rules of engagement that were fair and equitous. We said that countries using less than their share of the atmosphere could trade their unused quota and this would give them the incentive to invest in technologies that would not increase their emissions. But in all this, as we told climate negotiators, think of the local forest and learn that the issue of equity is not a luxury. It is a prerequisite.

I write this because it explains how little we know and how much we must learn. When Anil and I researched this issue and came up with the alternative formulation, we did not know much of the science of sinks. Could 'sinks' be divided in this way? Were we on the right track? Anil, I remember sent me to meet the top climate change scientists — handful then — to find out more. I came back no wiser — they all said truthfully to me that they had no idea if we could make this assertion. We went ahead and then rest is history. Our report was contested by WRI, not on the science but the politics.

This was the inconvenient truth.

This debate raged in the international circles. Our publication was read and cited to explain how global climate change negotiations must be shaped through the prism of equity. We were berated by the Washington club — the powerful NGOs who determine the discourse on global issues. But our politics have remained unyielding on this issue — climate change is about sharing the global atmospheric space and our right to development of all.

Our view of the science was infused with the politics of environmentalism of the poor from our world. Our view of global politics was borne out of the way 'goats' were kept out of common forests. It was only possible if people equally benefitted from the resources of the forests. This is where we then worked out our model of per capita entitlements and equity when it came to management of the other commons — the atmosphere. So, it was intensely political. But it was also scientifically rigorous.

This is where climate change demands a very different kind of scientific thought and enquiry — we need a combination of courage to speak with the knowledge we have today — and not wait for the final word to be known. We need the imagination to bring different worlds together. And we need politics of inclusive; justice and the rights of all people to be part of the science.

This is today's challenge. Take the crisis of climate change impacts as they are unfolding in our world. We know climate change science is young, being tutored and is evolving every day. We know much more today about what the future holds then we did yesterday; but the knowledge is still probabilistic and there are always too many other confounding factors. You cannot ever say that the cyclone was because of climate change; or that the flood that hit Punjab, Mumbai or Kerala or anywhere else because of the extreme rain was climate change. This is because the extreme heat or the extreme rain or the changing nature of the cyclonic activity or its growing intensification come on top of them because of gross mismanagement of our resources. So, the growing flood and drought intensity is certainly linked to the changes in rainfall pattern because of climate change. But it is also caused by development policies or the lack of these to manage water and land resources so that every drop of rain is harvested; so that water use is optimised through food systems that promote nutrition, livelihoods and biodiversity and that we remain mindful of the fact that extreme rain will need to be channelized and stored and not wasted.

This, therefore, needs the understanding of the politics of development — what is working and why not. It needs to be understood from the lenses

of people who are working in the field; it needs to be imbedded in the politics of marginalisation.

Take the catastrophic flooding of 2025 when Himalayan states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand and then the foothill, riparian Punjab have seen massive destruction of roads and other infrastructure. Mighty mountains have crumbled like rivers of mud. What is not normal is the intensity of extreme rain in this region. In August, Punjab had heavy and extremely heavy rain as classified by the Indian Metrological Department (IMD) for 24 days, out of IMD classifies heavy rain as more than 115 mm and extremely heavy as more than 204 mm in 24 hours [3, 4]. To understand this change we need to understand the globalized nature of weather. In 2025, during the period of intense monsoon activity, there were unusually high numbers of western disturbances — winds mostly originating from the Mediterranean bringing cyclonic activity and rain to our region. It is not clear why this is happening, other than the fact that western disturbances are linked to jet stream – winds from the Arctic. As this Arctic wind system weakens because of climate change, it is disrupting other linked global wind systems, including the western disturbance.

The weather disruption is due to a combination of factors, from the warming of the oceans; to the heating of Arctic region; to the decrease in the difference in heat between the equator and the North Pole and much more. This instability is now impacting us as we get floods from the skies. It seems that the revenge of nature is here. And it will stay and get worse.

It is for this reason that we cannot be complacent. We also cannot blame this on climate change and then say, in our usual fatalistic excuse of a way. The fact is climate change is about the emissions that we have burnt into the atmosphere for our economic growth and human greed. We are adding to this by deliberately and willfully making things much more, because of the way we do development. We are building in flood plains; we are not planning for drainage where we must; we are encroaching on vulnerable mountain regions; we are building houses, roads and hydropower units, without once thinking of the fact that these regions are seismic, that these are the world's youngest mountain ranges; that these slopes are made for landslides.

In all this, the role of today's scientific enquiry needs investigative and inquisitive minds. The scientist will get clues, and the answers will have to be worked on learning from scientific evidence, from plain common sense and from what can be observed in the real and highly complex world. It will require, most of all, active engagement with the world of ordinary people. It will need to pay careful heed to everyday events and

meticulous observation of scientific processes as they play out in our agricultural fields and forests.

Science of everyday things: growth but differently is the challenge

For us, in India we know today that this growth should be inclusive and then it will be sustainable. And if we achieve this, we get a double benefit — our actions to reduce local pollution and to drive green livelihoods will also reduce greenhouse gas emissions. In this way, our Nationally Determined Contribution (NDC), which puts together the package of actions to reduce emissions, would be based on co-benefits; development, if done right, will also address the urgent crisis of climate change. Take the issue of air pollution in our cities; it is a health scourge as toxins affect our bodies. The key source of the pollution is the burning of fossil fuels, in vehicles or industries that emit local pollutants like PM 2.5 or Nox. The agenda for clean air is to electrify our vehicular fleet and to ensure that only clean fuel is used for industrial applications. This transition to cleaner fuels and displacement of coal is good for our health and also has the added co-benefit of mitigating greenhouse gases. In addition, if we can make the leapfrog towards a mobility transformation – reducing the dependence on private vehicles we also have added benefits of cleaner local and global air. This is the co-benefit agenda that will work for us.

We know that it is in our interest to achieve this twin goal. We are vulnerable to climate change impacts. But if we do development differently by ensuring it is sustainable and inclusive, it would help us avoid the pitfalls of marginalizing actions designed solely for climate change. It would help us deepen the public acceptability for taking steps that may not be easy or convenient.

India, like many other countries, has to ensure growth. This means providing millions with food, employment, healthcare, education and housing, and increasing energy supply. This has to be our development priority. But development will require taking action that meets the needs of all. So this calls for a change in strategy. We cannot afford a capital- and resource-intensive pathway that adds to environmental degradation and inequity in society. We have learnt over the past decades that we cannot adopt the western-country approach to first pollute and then clean up. We just do not have the financial wherewithal to keep repairing the damage. We have to reinvent growth and this is what many policies in India have done: they have built inclusive sustainability as an outcome of the development policy. For instance, our policy to provide rooftop solar system at subsidized rates gives opportunities for local energy generation and livelihood support, but also a green transition. Similarly, Indian government's policy for pathways for decarbonizing the steel

or cement sector is about increasing circularity in waste materials like flyash and iron ore slag which improves the environmental pollution and also reduces the carbon intensity of these hard to abate sectors [5, 6]. This is the unique opportunity for countries like India—not to pit development against climate action but to subsume it within policies designed for growth.

For instance, we know we cannot solve air pollution without redesigning mobility because personal vehicles, however clean, take up road space and add to pollution and congestion. The western world has taken the path to subsidise and electrify personal vehicles, which is leading to disruption in industries as they strive to rework supply chains and redeploy labour for electric cars. We have the opportunity to think of another route—one that reinvents mobility so that we can move people and not cars. This means investing in electric buses and affordable transport like paratransit and two- wheelers. India's NDC must be about upscaling and integrating low-carbon public transport and not just counting electric cars. The policy is driven by cleaning up local air but has the added benefit of combating climate change. It is the same with the hard-to-abate industries. We know from experience that our industry will invest in technology that saves cost and increases competitiveness. The cement industry, for instance, switched to using fly ash, not to decarbonise but to use waste as raw material, substitute limestone and reduce costs of energy. The future of low-carbon industrialisation lies in similar win-win solutions, such as the reuse of waste materials from iron ore slag to biomass to refuse-derived fuel from municipal garbage—all designed to reduce the use of coal and other fossil fuels and to improve efficiency.

Most importantly, we must re-engineer the idea and design of a green economy. We cannot afford mouthing platitudes of green employment, knowing fully well that the renewable energy or electric vehicle transition, per se, does not mean more livelihoods. In fact, recent news shows that thousands of jobs have been lost in the UK because of the shift from blast to electric arc furnaces. This is why we see the pushback in western countries where much has been said without substance and this has prompted people, worried as they are about climate change, to care more about livelihoods.

India's opportunity is in the reworking of its economics so that local resources can be used for local livelihoods. If we do this, we can sequester carbon in trees and in soil, build resilience in society, withstand extreme weather shocks and also stem migration. We cannot afford an economy that is driven only by the gross domestic product (GDP), which extracts and exports produce, and not by gross nature product (GNP) that invests

in natural resources for livelihoods, locally. Our plan for climate change is the one that works for people and so the Planet.

Science for solutions that are inclusive, frugal and innovative

The challenge of science is not just to engage with the matters of everyday life, but to think of solutions that will work for inclusive and sustainable growth. For instance, every society must understand how the excreta it produces is managed. It teaches us many things about water, about waste, about technologies and about economics and politics: of who is subsidised to defecate in our societies? Today, the challenge also is that every society must connect the dots between the excreta it produces, the pollution it causes and the opportunity to reuse and recycle that waste so that it becomes a resource.

Remember, unlike the use of water in agriculture where it is 'consumed' for growing food, in the case of urban consumers or even industrial the bulk of the water is used, but not then discharged. Today, the discharge of effluent is adding to the water crisis by degrading available water through pollution. It is also adding to our health crisis. All this then points to the solution ahead — the way to take that 'wasted' water and make it 'used' water so that it can be returned to the hydrological cycle.

Over the years, my colleagues have studied the excreta sums of different cities. The city "shit-flow" diagram shows that the situation is grim as all cities either do not treat or safely dispose the bulk of the human excreta. This is because we often confuse toilets with sanitation. But the fact is that toilets are mere receptacles to receive waste; when we flush or pour water, the waste flows into a piped drain, which could be either connected, or not, to a sewage treatment plant (STP). This STP could be working, or not. In this case, the faecal sludge—human excreta—could be conveyed, but not safely disposed as it would be discharged into the nearest river, lake or a drain. All this will pollute. In most cities, this connection from the flush to the STP does not exist. According to Census 2011, the flush water of some 30 per cent of urban India is connected to a piped sewer. But our survey found that in most cases, these underground drains have either lost their connections—they need repair—or are not connected to the sewage plants.

That is why the focus has shifted to intercepting the sewage – not through capital intensive underground pipes but through tankers to transport this for treatment. The fact is that septic tanks are decentralised waste collection systems. Instead of thinking of building an underground sewerage network—that is never built or never completed—it would be best to think of these systems as the future of urban sanitation. After

all, we have gone to mobile telephony, without the landline. Individual septic tanks could be the way to achieve full sanitation solutions. The advantage also is the people are managers of these 'septic tanks' and so, if there is any overflow then it impacts their surroundings and will call for desludging operators to empty the tanks. The key policy intervention is to ensure that the private desludger tankers are 'regulated' so that they not only collect the 'faecal sludge' but also take it to treatment plants. This is what is being done in different states of India through installation of GPS tracking systems and penalties on non-compliance.

But there will always be an issue of local hygiene due to overflowing septic tanks and transport of faecal matter to a processing plant And cost/footprint of transport. Implementation may be an issue and I see a shit-mafia like sand mafia in operation

For enabling this transition, the Government of India has made changes in policy and now practices — it has recognised that these on-site systems exist and need to be incorporated in sanitation plans. Two, they are providing regulation for the collection and transportation of faecal sludge business so that waste is taken for treatment and not dumped somewhere. And most critically, city governments are working on the treatment system for faecal sludge – which in turn will reduce the pollution in rivers and lakes. But now the challenge is that we must reuse this treated water.

This is where the real opportunity lies. The fact is that this treated water and sludge is nutrient rich. Today, the global nitrogen cycle is being destroyed because we take human excreta, which is rich in nutrients and dispose it in water. In this case, we can return the human excreta back to land, use it as fertiliser and reverse the sanitation cycle. The treated water or faecal sludge, after treatment, can be given to industry or cities to reuse as water and farmers for soil enrichment. But this also means that we need new standards to be set for reuse of treated wastewater – so that basic nutrients needed for land are not lost in the treatment. This approach makes the users of this treated water the agents to ensure compliance with standards. Water to Water. So, we can be water-secure, because we are water-wise.

These are planetary matters that are critical in our world and that need the best of science, the best of innovation and the very best of engineering. This must learn from the frugality and wisdom that nature teaches. We are living in the age of climate change. We are living through the catastrophic times that will bring even mighty mountains to their knees. The time for human arrogance, denial and mindlessness is over. This is our challenge. Our common future.

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Nurturing Academic Creativity in India: Hopes for the Future

Sunil Mukhi

Scope

Creativity is a precondition for doing basic science which, in turn, is a precondition for developing advanced technologies that benefit society. With a brief historical background, I discuss what needs to be done to build a creative environment and promote fundamental research in India. Working together, government, industry and academia should understand the role of basic science discoveries in our daily lives, recognise the need to invest in fundamental research, remove unnecessary obstacles to creativity and build a mature and reliable research ecosystem where creativity is valued and supported.

Nurturing creativity

There is a notion that creativity blossoms on its own in surprising ways, that it cannot be harnessed and will inevitably flourish on its own. A familiar example is seen in the life of Srinivasa Ramanujan, who made profound mathematical discoveries despite growing up in isolation and without any real mentorship. However, Ramanujans are extremely rare. Many lesser mortals have the potential to be creative, but how they actually perform depends a lot on their environment, which determines how effectively they realise their potential. Creativity flourishes in certain cultures, while in others it is suppressed or just ignored. Hence to nurture creativity it is important to understand what its needs to flourish, and how this can be provided.

India today is a mix of opposites. We see immense creativity among ordinary people who find practical solutions to the problems of daily life, yet we have lived for long with stifling levels of bureaucracy and top-heavy administration. We have a strong and sophisticated scientific community with high points of excellence and international recognition, yet the

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average quality of scientific work is not as high as it should be. Our society is liberal in some ways, conservative in others. We are simultaneously eager for change and frightened of it. This is a time when the direction we choose will decisively impact our future. What does it take, at the level of both scientists and governments, to nurture creativity in our country – and in doing so, facilitate the financial and humanitarian progress that the nation urgently needs?

The discoveries that influence us today

Let us briefly survey the landscape of major creative discoveries. The early 20th century witnessed two conceptual revolutions in science: quantum physics and (special and general) relativity. These were responsible for a large fraction of the developments that followed: atomic structure, chemistry, semiconductors, superconductivity, lasers, nuclear power, materials science, quantum field theory, particle physics and cosmology, which in turn have provided impetus to more recent pursuits such as quantum technologies, quantum materials and gravity-wave detectors. Other conceptual advances came independently from the theory of information and computing, which gave us algorithms, networks, machine learning and most recently an explosion in artificial intelligence. In biological science, the discovery of evolution and the unravelling of genetic structure provided a deep understanding of the chemical basis of life, and thereby led to enormous social benefits in both agriculture and medicine.

A small fraction of these developments originated from work done in the Indian subcontinent, and it is important to recognise that fraction. In Physics we had quantum statistics (S.N. Bose), the Raman effect, cosmic rays and positron theory (Homi Bhabha), thermal ionisation (Meghnad Saha), space research (Vikram Sarabhai) and the early work of S. Chandrasekhar on stellar structure (his later work was done abroad). Similar levels of creativity can be attributed to J.C. Ghosh and P.C. Ray in Chemistry and to J.C. Bose and G.N. Ramachandran in Biology. This is only a short list — many more individuals made significant discoveries at a high level.

Three factors can be examined to assess how and to what extent this quality of research was possible in India, at a time when the country was still mired in poverty and faced enormous challenges during and after colonial rule. One is undoubtedly the innate talent, passion and optimism common to all the named individuals. They were driven and determined to overcome any obstacle in the attainment of their science goals. The second is the rich intellectual tradition that inspired them – most of the scientists named above spoke strongly of their inspiration from cultural

and historical sources of our subcontinent, particularly the Mimāmsā, Nyāya and Vaiśeṣika schools of thought originating around the second century BCE that advocated logical rigour and rationalism.

The third factor, namely support from the Government of India as well as private industry, is a more uneven story. Research in pre-independence India was largely a tale of colonial indifference, but philanthropy played a modest positive role. Post-independence, government support grew and was famously boosted by Pandit Nehru's passionate advocacy for "scientific temper" as the way forward for the nation. Funding was particularly generous for the programmes led by Bhabha and Sarabhai. This support went primarily to national missions like atomic energy and space research, both of which contributed enormously to national sovereignty in science but perhaps not as much to world-class innovation. At the same time, basic science institutions were also set up in this period that continue to flourish and lead today.

Coming now to more recent times, let's look at a few key research activities that symbolise the current era: gravitational wave detection, gene editing and synthetic biology, quantum materials and technologies, and artificial intelligence. How much has India contributed to these? Some positives can be highlighted: genome-edited rice varieties have recently been unveiled, while a gravitational wave observatory is being built in Maharashtra and high-quality research papers have been published on quantum materials and prototype devices. These and other projects are highly collaborative, a sign of the times we live in where so much of science is global. But one has yet to see recognisably Indian/subcontinental schools of scientific research that are transformative in nature.

The importance of basic science

This brief and simplified historical survey sets the context for a key point that must be appreciated in order to build a stronger future for India: we have an outstanding tradition of excellence in basic science, a key part of R&D that has a unique role as well as unique needs. This area has a greater transformative effect than is commonly understood, and indeed the prosperity of the developed countries is closely linked to their earlier investment in fundamental research.

However, unfortunately the trend today across the globe, including in India, is to move away from it towards "applicable" or "translational" science. We see policy pronouncements and initiatives aiming at orienting all scientific research towards the direct benefit of society. While there is no doubt that huge investments in this direction are desirable (and this is where industry must play its part), it would be a grave mistake to think

that this alone is the best way to transform society. We should not forget that at the start of the 20th century, all the efforts of medical science to deal with bullet wounds and broken bones were upturned by Wilhelm von Roentgen's accidental discovery of the x-ray, which instantaneously became the default diagnostic tool for such injuries. Nurturing creativity will create the space for such "accidental" discoveries in the future that could produce novel methods to solve today's serious crises of energy and the environment.

This point is eloquently explained in the book "The Usefulness of Useless Knowledge" by Abraham Flexner, founder of the Institute for Advanced Study in Princeton, which is highly recommended reading for science policy makers everywhere. In India, this issue was most eloquently explained by the legendary scientist and science adminstrator Homi Bhabha, founder of the Tata Institute of Fundamental Research as well as the Atomic Energy establishment, who said: "Pure and applied research are but two stages in the historical development from ignorance, through knowledge, to control, of the phenomena of nature in any given field. There is, therefore, no question of differences in practical importance between the two categories of research. One should rather look upon 'pure' research as long-term research, while technical research, being historically the later stage in any line of development, may be looked on as short-term research."

The exciting developments of the current era all draw heavily from the breakthroughs in fundamental science of the early 20th century. In contrast, the 21st century has not led to comparable fundamental breakthroughs on which future generations will be able to draw. One often hears that basic science has reached a dead end and nothing more can be done beyond exploiting it for social benefit. This defeatist notion has been propagated before, but failed spectacularly. In 1894, in a speech at the University of Chicago, Albert Michelson said: "it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles." He soon turned out to be completely wrong, when his own legendary Michelson-Morley experiment led to overturning the very same underlying principles of which he spoke. The result, thanks to the subsequentwork of Einstein, was special and general relativity, without which many modern technologies from cancer therapies to nuclear energy to satellite communications and GPS would be impossible. The lesson is that it is unwise to predict the end of path-breaking science, a wise society will instead support its continued progress.

For this reason, an important fraction of research budgets must be dedicated to basic science. This requires policy makers to have an

enlightened outlook towards risky or blue-sky research. While industry has in the past contributed to such activities (for example, the laser was invented at Hughes Research Laboratories in the US), one cannot necessarily rely on it since the outcomes are speculative and long-term. It is up to the government, under the advice of its best scientists, to continue supporting research that alone can radically transform society but whose success may be hard to predict with certainty.

On the topic of research budgets, it is instructive to examine some basic economic data, starting with the current R&D expenditure of different economic units as a fraction of GDP[1]. For the US, China and the European Union, the figures are presently estimated at 3.5%, 2.4% and 2.3% respectively while India comes in far lower at 0.64%. In absolute terms the figures are even more unfavourable to India due to its lower overall GDP. If now we consider the breakup of this expenditure into government and industry contributions, the picture changes somewhat. In the first three cases, the ratio of industry to government contribution is around 3 or 4, while in India this ratio is far smaller, barely a half. If, hypothetically, Indian industry were to suddenly ramp up its R&D expenditure to a similar ratio as in these other countries, Indian R&D outlay would jump to a more respectable 1.7-1.9% of GDP. Even then it would be relatively small because of our GDP and the size of our population, though much better than the current figure. In short, an enhanced contribution from industry is urgently needed and long overdue, but increasing the government's R&D investment is also absolutely essential.

Specifically with regard to the basic science component, today significant investment is being made in the US, the European Union, Japan, South Korea and China, with the US leading at the moment. However the trajectory of US policy presently seems a little uncertain and it is thought that China will rise to the top, though its current investment in fundamental research is only 7% of its total R&D budget while the corresponding figures for the US and the EU are 15% and 23%. Indian comes in at an apparently respectable 14% of total R&D, but again because of our much lower net R&D investment, China ends up spending 8 times as much as India on basic science — 32 billion *vs* 4 billion US dollars. At this rate we have little chance of ever competing with China.

Cultural and administrative factors

While funding is necessary to ensure a high level of creativity in the modern world, it is far from sufficient. Cultural factors pervade government

1 The figures cited here are approximate and may not be up-to-date in all cases. Some primary sources are given in Refs 1-4.

as well as the academic community and it is important to appreciate and address them. India's rich legacy of rational knowledge systems, as mentioned above, can potentially be an asset. But we are also ridden with class and caste divisions, geriatric leadership, and a colonial legacy, which are responsible for some endemic problems that need to be addressed.

On the topic of geriatry, it is notable that while a country like Austria recently had a 31-year old leader (Chancellor Sebastian Kurz), it is hard to imagine someone of this age in India being entrusted with responsibility for even a small department! We need to focus less on age and more on competencies.

The nature of interaction between government and academia is in crucial need of improvement. Thanks to digitisation and the internet, certain aspects of transparency in governance have improved in recent years. However, politicians and bureaucrats who take policy and funding decisions need to interact more meaningfully with academics, particularly with the youthful component from where our future leaders will come. Governance is enriched by hearing multiple views and trying to understand them with an open mind. Reform in this direction could come from a more layered structure of representative committees and a more equitable gathering and rational synthesis of inputs. Grant proposals or faculty hirings should receive inputs from a wider selection of peers, after which the most well-reasoned opinions are taken seriously. A spirit of trust, openness and equality must be brought in between government, bureaucracy and academia. It will greatly help if the agencies that deal with higher education are staffed with academically well-qualified and highly motivated persons, as is typically the case in the developed world.

We must dispense with bureaucratic restrictions that are academically indefensible. For example faculty appointments in India are typically subject to rules like "must have first division in previous degree" or "must have X years of experience in lower grade" "must be below a certain age". In the creative world, such rules are unhelpful and actually damaging: Dorothy Hodgkin and John Gurdon both got second-class degrees in college, and each of them went on to win a Nobel Prize, yet they could not even have been hired in most Indian institutes! A brilliant researcher like mathematician Manjul Bhargava became a full Professor of Princeton University at the age of 28, but this again would be impossible in India. We urgently need to remove such poorly conceived restrictions.

Restrictions on financial activity likewise can be very burdensome and slow down the pace of research. This is a difficult issue since there has to be accountability to the taxpayer and a sincere effort to avoid wastage. But with trust and goodwill, it is possible to have both responsibility and

the freedom to pursue one's mission. For this, the focus has to shift away from micro-managing small expenditures, to the broader assessment of whether set targets have been achieved. The goal of doing good science needs to always be kept at the forefront.

These prescriptions for government need to be matched with an equal effort from the academic community to rethink its own approaches. The kind of barriers described above (like age and previous experience) are not constructed only by bureaucrats but also taken for granted by senior academic leaders. They should be sufficiently motivated towards excellence that they avoid creating barriers to it, and in fact perceive themselves as enablers of that excellence. They also need to make a sincere effort to broaden their own understanding and perspectives about science itself. To be an effective Director/Vice-Chancellor/Dean, two different qualities are essential: an excellent research record in a specialised area as well as a broad understanding of the key issues in modern science cutting across all subjects.

Leaders must have the motivation to update their breadth and understanding regularly and motivate the community as well. They should engage in regular discussions from the ground up with all stakeholders. Bluntly, we cannot afford to have our institutions run by leaders who insulate themselves behind locked office doors and only meet each other. We also cannot afford to be surrounded by procedural roadblocks to every initiative. Our institutions need regular faculty meetings where leaders actually consult their faculty, apprise them of developments and challenges, collect recommendations and write careful minutes that are later enshrined as policy. Only then will all stakeholders come to feel a sense of responsibility for institutional outcomes. The culture of excellence seen in a few Indian institutions can be traced to this sort of consultative decision-making.

Of course some of the restrictions we see on hiring, budgets and spending have arisen because of (intentional or careless) misconduct in the past by various types of stakeholders including junior ones. Fiscal responsibility is a non-negotiable part of being an academic. We also have the cyclic problem that the government's low trust in academics creates mistrust on the other side as well. It will be a great asset to creativity if we can mentor faculty members from a young age to develop leadership abilities, including critical thinking about science as well as a sound understanding of budgets and management.

Academic conservatism

The conservatism of our academic environment towards science itself is also a major issue in need of redress. Historically we have often

been slow to grasp the importance of new developments in science and technology – for example mobile phones and the internet were initially opposed by policy makers in India who argued, incorrectly, that they would only benefit a small elite! From that point of view, things have improved – modern India is much quicker to adopt new technology and ideas. Yet, our academia has not demonstrated sufficient urgency to engage with new developments in science. In fact there is a remarkably widespread – and depressing – tendency to favour safe and predictable research trajectories and even oppose the introduction of new ideas and higher standards of achievement.

As an example in Physics, the modern area of topological materials, with all its ramifications from experimental to mathematical, does not seem to have grown in India as rapidly as it should have, with most Physics departments still invested in pursuing relatively routine and unexciting questions instead. Another case in point is Artificial Intelligence. This has not exactly taken off within Indian academia despite decades of research in the field and the explosion of interest in recent years. Some needed steps have been taken by the government, with roadmaps and advisory papers starting in 2018 and the cabinet-approved and funded IndiaAI mission getting off the ground in March 2024. Yet, behind the announcements, position papers and mega-conferences one hopes for something more technical, concrete and meaningful. What will creativity mean in the age of AI, and how does Indian science plan to address this? How will teaching be transformed? What types of research will thrive and how should we adapt? How should the ethical issues of AI be addressed and what policies and laws need to be made in this regard? The Academies can, and should, play an important role here by initiating discussions and producing working papers on these issues.

Academic ethics

The final topic that will be addressed here is academic ethics. It is no secret that, while the highlights of Indian science are respected around the world, the average ethical standard of our academia is perceived poorly. We have the dubious distinction of ranking high in lists of papers retracted for misconduct, plagiarism and data manipulation. Ethical misconduct spells the end of credibility of a scientific enterprise, making creativity an unattainable goal. To remedy this, all Indian institutions need to have an academic Code of Conduct and an Ethics Committee that implements this Code through training as well as honest investigation of alleged misconduct. The ethical outlook of an Institute depends crucially on its top leadership, which has to ensure that the Office actually does its job without fear or favour. A national Office of Research Integrity with members of unimpeachable ethical standing is also a must.

A very modern and vexing problem is that of ranking systems which assign numerical values to the achievements of different scientists and institutions. The importance given to these systems has led a rise in mediocre short papers with self-citations and mutual citations as these are easy ways to rise in a ranking system. Yet it is plain to see that they do not deserve to be counted on par with slow, difficult, creative research that has an actual impact on knowledge. Evaluating research in terms of simple numbers, and then taking policy decisions based on these numbers, will severely damage our scientific enterprise. Good research will be swamped in a landscape of sponsored mediocrity, and we will find it difficult later on to distinguish one from the other. Evaluating creative work must be done with patience, skill and effort — all of which are available in our community if we only choose to harness them.

The issues and prescriptions highlighted above can be summarised into one major task, to be collectively shared by government, industry and academy: the nurturing of creativity. It will be enough if we move our mindset out of its comfort zone and pledge to recognise, mentor and support creative work. The rest will flow on its own, and the benefit to our country will be incalculable.

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Strengthening Science Education and Research

Srinivas K. Saidapur

Scope

The scope of higher education, and number of higher educational institutions (HEI — colleges, universities, premier institutions like the IISc, IITs, IIMs, IIITs, IISERs, etc.) imparting education in basic sciences, engineering and technology, arts, social sciences and humanities, agriculture, health sciences, law, and other areas expanded progressively in relation to growth of population since India's independence in 1947 with just 17 universities. The population of India at the time of independence was just around 35 crores (~350 million) and now it is around 146.39 crore (1.46 billion in 2025) with well over 1300 universities and 50,000 colleges. The total number of universities, colleges, and premier standalone institutions (higher education institutions or HEI) is over 70,000 now (source: Google). Many colleges that once offered only undergraduate courses, now offer postgraduate and research degrees. Thus, expansion of HE system in India is amongst the world's largest. The expansion accompanied the slogan: *access*, *equity* and *excellence* to promote inclusion of socio-economically backward classes, the disadvantaged section of the society. In the process, 'access' and 'equity' could be largely accomplished, but 'excellence' eluded for want of refinements in the policies, academic flexibility, institutional autonomy, faculty deficiency, quality governance and leadership. Institutions failed to guard against inbreeding and mediocrity in the appointment of faculty. In effect, the educational institutions saw a progressive loss of hybrid vigour, aging, and withering of excellence.

Initially, in the early post-independent India, both Central and State government-run universities had a good degree of autonomy, academic freedom and competent faculty drawn on an all-India basis, all of which ensured upward growth and development. The HEIs then

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enjoyed good governance and academic leadership of institutional heads, the Vice-Chancellors/Directors/Principals. After about the first 25 years of existence, faculty appointment became mostly local-centric and foreshadowed inbreeding. At the same time, State-run universities were taken over by the respective States in the last quarter of the past century, paving way for direct political control and interference by the respective governments. Consequently, in the 3rd quarter of their existence, many universities visibly lost their glory of imparting quality education, and credibility of their credentials due to poor quality outputs.

Several factors have contributed to the present pathetic state of universities and colleges. Prominent among these are: poor or obsolete infrastructure, inadequacy of faculty (number and quality), abysmal funding, erosion of institutional autonomy, poor vision, lack of foresight for institutional growth, political dominance (control and interferences), and maladministration with unwanted controls that compromised on the enthusiasm of faculty in performing at their highest levels of academics and research. In short, universities lost their academic ambience, fervor, and vibrancy in the very 3rd quarter of their existence. Majority of state-run HEIs have now become directionless for want of autonomy, visionary leadership and quality governance. Even universities set up by the Central Government 10-15 years ago are yet to take-off and make their existence felt to justify the tax payer's money spent on them. Most HEIs have now become infertile and their credentials have lost credibility. The universities with over 75 or more years of their existence which once enjoyed high reputation, have now become relics! It is depressing to see the unpreventable decay of HEIs, a man-made disaster with rare exceptions in just about 75 years! Whereas, Oxford and Cambridge universities have sustained quality consistently for about or over 1000 years and are still going strong. India should learn from such institutions to raise the standards, sustain quality of teaching and research in its HEIs.

Further, a steady decline in academic growth and quality research in the past 2-3 decades is even more alarming. The HEIs simply failed in maintaining and sustaining a vibrant ambience/vigor of youth, due to defective policies of the prevailing governments and practices (e.g. recruitment of most competent faculty, funding etc.). Instead, HEI were let to age freely. This is in stark contrast with the Western/European or American universities which draw talent from all over the globe to remain relevant, vibrant and academically on top. A worthy academic and administrative ecosystem enthuses them to perform to their best. On the other hand, the rule heavy and insensitive administrative ecosystems convert bright minds to bonsai and subservient academicians which is very evident now in India. Loss of credibility of credentials is now a

serious threat to the existence of universities. Besides, restoring credibility of varsity credentials is clearly an uphill task. Unless hard decisions are taken and implemented, it is impossible to restore higher education to any meaningful status or rank.

In recent times, following the digital revolution (IR 4.0) and its far reaching and massive impact, compulsion for global standards of education and research, and cultivating the culture of innovation have intensified. At the same time, aspiration of Gen-Z population for global citizenship has grown colossally. In any case, future global developments rest on science, technology, and innovations as they have indispensable roles in every aspect of human life and day-to-day transactions of various kinds. Even future wars will be fought largely using knowledge based innovative technologies rather than huge man-power. Major causes of fall in higher education and research are the following:

1. Obsolete Curriculums
2. Inadequacy of Faculty (Quality & Quantity)
3. Outmoded Infrastructure
4. Abysmal Funding
5. Lack of Academic Vibrancy
6. Repetitive or mundane research, plagiarism, publication in the predatory journals and so on due to unwarranted focus on publications and citations indices.
7. Lacklustre, directionless and incompetent choices for Academic leadership of institutions, devoid of vision and academic sagacity
8. Excessive Political Dominance (Control / Interferences)

However, a concern of fundamental importance is that developments in science & technology largely determine progress and prosperity of any country. So, strengthening science education and quality research is cardinal to the development of India that encompasses as much as 17.78% of the world population (source: Google).

In the following passages some suggestions are presented for developing possible corrective measures to reset higher education infirmities. These call for difficult and well-reasoned decisive measures for cleansing the rot and set the house in order. Here, I focus on the issue of redesigning science courses with a view to generate discussion and debate to build consensus on the need to evolve *novel courses* for furthering science education and research of global standards. The Indian National Science Academy (INSA) may play the role of a *catalyst* in reshaping science courses and curriculums for graduate/postgraduate education.

In recent decades various subject domains (science, social sciences and humanities) have grown significantly leading to the understanding

that they possess no more sharp boundaries with their subdisciplines, and allied subjects. This is more apparent as far as biology is concerned. For instance, the borders of biological subjects like botany, zoology, microbiology, biochemistry, and biotechnology have now become highly porous or even borderless. Similar is the case with: geology-geography-atmospheric sciences, sociology-anthropology-social work, economics-commerce-business management, political science-public administration-international relations, and so on. Besides, to gain proficiency in these subjects they liberally utilize mathematical and statistical implements. Likewise, knowledge of evolutionary biology is pivotal for a good grasp of social sciences because knowledge of human behaviour and principles of evolution provide insightful information on origin and evolution of human society, spread of religions, crimes, progression of economy, and so on. Thus, there is a need for an integrated and seamless interdisciplinary approach through novel curriculums/courses with a global outlook to grasp the intricacies and underlying principles of: material sciences, biological sciences as well as social sciences and businesses [1]. The entire edifice and the style of science education have to change. On the other hand, building rigid domain walls between the subjects will only undermine the true significance and potential of concerned knowledge domains.

A major issue that is hurting quality education is the use of outdated curriculums that are not of global standards or at par with modern requirements considering growth, expansion and scope of various subject domains. How do we go about building meaningful transformational pathways for strengthening science education and research? A first step in this regard will be *disruption* of the existing, and designing new courses with integration of seemingly disjointed but closely related and/or needed subject domains. Equally important is adoption of global standards of teaching-learning-assessment pedagogies. Universities and various premier institutions involved in science education and research should be encouraged and mandated to undertake interdisciplinary approaches. A broad and integrated approach will go a long way in greater appreciation of fundamentals by the students; it will also eventually lead to a training of minds for quality research and innovation [2].

Poor knowledge of fundamentals of a given subject is a greatest predicament of modern graduates, postgraduates and doctoral degree holders of all streams. University Grants Commission (UGC) and other regulatory bodies should seriously think of revamping curriculums of all streams, emphasizing the importance of reintegrating disintegrated subject domains, along with customized courses of mathematics and statistics. The flavour of mathematics and statistics will not only help a better grasp of fundamentals, data collection and analysis, but also in developing models, hypotheses, theories and making future projections.

Apex bodies like INSA (and other academies) can play the role of a *catalyst* in promoting new approach towards teaching and learning processes of science subjects.

To facilitate the strategy described above, the HEIs need to opt for a 'school system' and offer degrees with integrated subject domains and flexibility for a student to make choices. A given teacher may belong to a school but performs with a general engagement. For instance, teachers belonging to mathematical sciences may teach customized courses for students of different streams. Experts in biochemistry/genetics/molecular biology/bioinformatics, or evolutionary biology may teach students of all biological sciences. Such an approach will deepen the grasp of fundamentals, and encourage undertaking cutting edge researches and collaborations.

As far as research is concerned, India needs a clear policy to support quality research of high standards and relevance. Any good research will 1) shed light on some fundamental aspect of a given subject domain, or 2) elucidate a new and unknown phenomenon, or 3) help develop new technologies or make innovations. Mundane and repetitive research with no consequence needs to be discouraged. Plagiarism, retraction of publications, publication in predatory journals should be viewed as serious offences and dealt with accordingly. The focus on quality over quantity needs restoration.

To be brief, INSA may constitute expert panels to develop model integrated science courses with sound reasoning and then persuade various regulatory bodies (UGC, AICTE, MCI, etc.) to promote adoption of novel courses and curriculums in their affiliated institutions (colleges and universities). In addition, INSA may prevail upon the regulatory bodies and funding agencies to focus on ensuring quality research through clear-cut policies as detailed above.

My next suggestion pertains to lecture workshops held jointly by the three science academies (NASI, IAS, INSA) for promotion of science education. These are monitored by the Indian Academy of Sciences (IAS), Bengaluru. Therefore, the IAS can take up the issue of developing integrated science courses/curriculums through brainstorming meetings with members drawn from the fellowships of various science academies and constitute panels of experts. It may also specifically encourage holding lecture workshops with a *specific theme* emphasizing the importance of *integrated* approach in better understanding the fundamentals of a given subject domain; for example, holding a lecture workshop on 'Animal-Plant Relations' or 'Developments in Material Science' or 'Applications of Mathematical Sciences in Biology' etc.

Of the eight factors affecting science education and research listed in the beginning, I have addressed only curricular aspect in detail. The other factors listed above (such as recruitment of faculty, funding and so on) are also very important but they may be beyond the purview of INSA. Yet INSA and other science academies including social science academies may jointly prevail upon and convince the various regulatory bodies (UGC and others) to take cognisance of these issues so as to encourage high quality in teaching and research. Obviously, the regulatory bodies can address these issues effectively.

Lastly, I am happy that INSA is bringing out a *Legacy Volume* in celebration of its meaningful and commendable journey of 90 years. Surely efforts of INSA have gone a long way in promoting science and scientists. At 90, it is befitting to reflect on the way forward for promoting and sustaining quality science, and heralding the culture of making innovation habitually in both teaching and research. Let us not forget that strength of future India lies in the development of science & technology to global standards.

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Evolving Responsible Research Assessment for a Healthy Academic Ecosystem

S.C. Lakhotia[1] and A.K. Singhvi[2,3]

Scope

Promotion of science, a major objective of the Indian National Science Academy (INSA), involves recognition of quality research output and development of policies for fair, transparent and responsible research assessment. The current processes of academic assessments in India tend to rely largely on quantitative parameters. Since these are relatively easy to manipulate, recent years have witnessed widespread use of deceitful unethical practices by academic institutions and individuals to attain higher 'ranking'. Such unethical acts collectively undermine the country's academic system and eclipse the truly bright spots of quality education and research. It is, therefore, necessary that radically new evaluation and assessment systems are developed that rely on quality of work done rather than only on quantity. Several suggestions are made here for quality-based assessment systems for individuals, institutions and research project proposals. It is expected that INSA, being a premier science academy of the country will take a leading role, in synergy with other academies, academics and regulatory bodies, and evolve appropriate guidelines for implementation.

Introduction

Promotion of science, one of the most important requirements for a wholesome progress of the society and country, has appropriately been the first objective and a major activity of the Indian National Science

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Academy (INSA). Science promotion has two broad positive components: i) recognition of quality research output in basic or applied disciplines, and ii) articulation of inputs for national policies by preparing policy documents and 'white papers' for use by the regulatory and other agencies in the country that regulate and promote the actual conduct of research and its output. Since its inception, election to fellowship and conferment of various recognitions have been a significant component of INSA's science promotion activities. Contrastingly, however, the academy has not been as proactive, as desired in the articulation of policies for science promotion to cater to the nation's needs.

A different facet of the promotion of science and scientific temper is the development of criteria and policies for identifying unethical acts by individuals and institutions in the conduct and dissemination of research, and suggesting appropriate procedures for penalizing unwarranted actions in such instances. To this end, INSA published a collection of articles on different aspects of ethics in conduct and governance of science in 2019 [1].

The issues discussed here outline the expected roles of INSA in developing an ecosystem for promotion of 'healthy' and ethical research practices and scientific temper, which cardinally involve timely, objective and responsible assessment of research output. We first consider limitations and pitfalls of the current evaluation system in India, and thereafter, suggest the desired changes in recognition and promotion systems.

Current practices in assessment and recognition of research output

A timely recognition of talent, besides being an important source of encouragement to the individual, also empowers and enthuses him/her to be proactively involved in catalyzing quality research and promotion of scientific temper in the community and society. *Sensu-stricto*, recognition of an individual is based upon assessment of the quality and impact of her/his research output, reflected primarily in the published research articles and/or the derivative applications like patents and products. An additional component of recognition is the social outreach of individual's academic activities.

a) Quantitative vs qualitative parameters for assessment

There are two facets of assaying the research output — quantitative and qualitative. As these terms indicate, the quantitative facet measures numbers of publications/patents, journal impact factors (JIF) and citations, while the qualitative parameters examine the academic or

applied impact in terms of actual advancement of basic and/or applied knowledge, i.e. examine what is published rather than where it is published and, for applied research, assesses the actual translational impact, rather than just counting the numbers of patents filed and granted but never actually used.

Since research activity is now more or less mandatory for the under- and post-graduate students and their teachers, the numbers of researchers, research articles and journals have increased manifold. Further, since the research publications are now an essential component to qualify for a doctoral degree, for appointments, for promotions, for recognition, for awards, and for institutional rankings, the pressure on those tasked with their assessment has also increased significantly.

Currently, quantitative parameters are nearly universally used in assessing the research output as these require minimal human effort and time, and are believed to be objective. The persuasively sustained publicity by commercial databases like SCOPUS and Web of Science (WoS) also has unfortunately convinced those involved in various assessments that the quantitative parameters provide optimal and objective reflection of the individual's or institution's research achievements. Consequently, publication metrics are considered as a reliable proxy of the quality of research output. This is despite the fact that the two are not equivalent to the two faces of a coin.

b) Damaging consequences of excessive reliance on quantitative parameters

Unethical conduct in research has existed since time immemorial, but the scale at which it is increasing during the past few decades is alarming. Excessive reliance on quantitative parameters has indeed stimulated an increase in the numbers of research publications. Unfortunately, however, these have concurrently also encouraged and nurtured unethically conducted and communicated research. Although a global phenomenon, many recent analytical studies have highlighted the situation in India with respect to unethically conducted and/or communicated research to be alarming indeed [2-12]. A recent bibliometric analysis [7] revealed that during 2018 to 2024, the numbers of publications of seven relatively young Indian universities showed an unusually high increase (varying between >243 to 766%) (Table 1). Such increases helped these universities to secure high institutional ranking. However, such unusual spurt in numbers of published research articles has been accompanied by equally unusual higher numbers of retractions of publications from these universities (Fig. 1) as the publishers discovered a range of unethical practices during publication of the retracted articles. In comparison,

Table 1: *Comparison of increases in research outputs of study group of universities and a control university in India during 2018 and 2024*

University (year founded)	Type	Number of articles published		% of increase in numbers of articles from 2018- 2019 to 2023-2024		World ranking for total number of published articles	
		2018-2019	2023-2024	Institution	Country average	2018-2019	2023-2024
1 (2012)	Study Group	521	4,478	760%	50%	1500+	601
2 (2010)		331	2,865	766%	50%	1500+	941
3 (2010)		383	3,070	702%	50%	1500+	888
4 (1980)		625	3,823	512%	50%	1500+	958
5 (2005)		1,503	5,160	243%	50%	1164	514
6 (2005)		3,037	10,418	243%	50%	656	187
7 (2003)		489	2,662	444%	50%	1500+	1000
8 (1909)	Control	4,124	4,556	10%	50%	480	587

Data adapted from [7] with suppression of identities of the universities. The university # 8, used as reference control, is a highly acclaimed academic institution in India that has shown a steady growth.

a long-established institution of higher education in India with an international acclaim for its academic performance, recorded only a modest 10% increase in its publication metrics during the same period. Thanks to the quantitative parameters used by the institutional ranking platforms, this institution was ranked far below the above universities which recorded high volumes of research publications, albeit of uncertain quality. A comparison of the Research Integrity Risk Index, that measures the retractions and publications in delisted journals [7], revealed that out of a total of 50 universities from across the world with a very high Research Integrity Risk Index (red-flagged), almost one third (16, see Table 2) were from India (this group also included the 7 universities noted in Table 1 and Fig. 1). It is to be noted that this analysis was restricted to journals that are/were covered in the commercial databases like SCOPUS and Web of Science (WoS). *Since a huge number of so-called 'research journals' published from India and elsewhere remain outside these databases, the proportion of unethically published research articles in the country is likely to be much higher.*

This deplorable state reflects 'gaming' on part of institutions of higher education to exploit the quantitative parameter-based assessments used by the diverse institutional ranking platforms. The over-whelming pressure to 'publish or perish', and the convenience of manipulating quantitative parameters used for the assessment of research output cause damage on multiple fronts. On the one hand these incentivize the researchers and institutions to use fraudulent practices to improve their

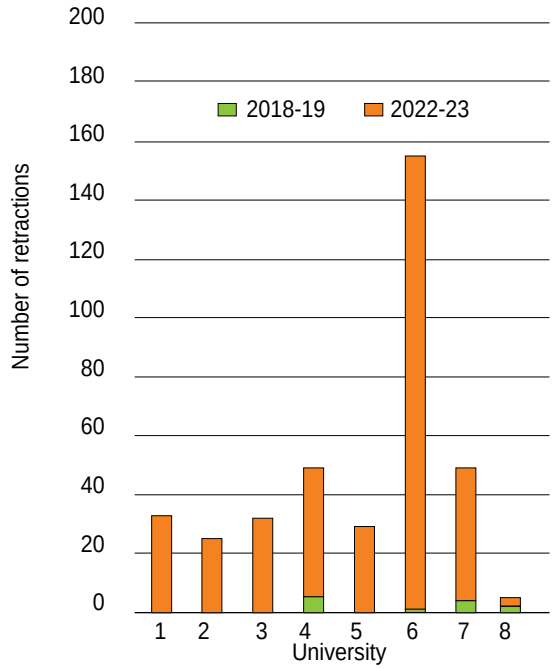

Figure 1: *Comparison of Retraction counts of the 7 study group universities and a control institution (#8) of high academic reputation from India (serial numbers are same as in Table 1) in the years 2018-2019 and 2023-2024. Figure adapted from from [7] with suppression of identities of the universities.*

publication metrics, and on the other, these also encourage, editors of research journals and their commercial publishers to indulge in diversity of unethical or outright fraudulent activities. A more serious long-term damage is the training of young researchers under such unethical research environment. Ironically, the conventional unethical acts like plagiarism, data/image manipulations etc., now stand dwarfed by the unethical practices associated with the mushrooming of predatory journals, the 'paper mills' and their 'brokers' [10, 13-15].

Taking advantage of the 'publish or perish' situation and the contemporary money-driven research publication ecosystem, 'paper mills' are actively churning out huge numbers of fraudulent research papers. Unfortunately, some journals 'indexed' in SCOPUS or WoS also get involved in 'paper mill' activity in return for a mutually agreed payment. The lure of money and the 'reward' of greater number of publications has resulted in nefarious collusions between authors, institutions, peer-reviewers, editors, paper mills, some established publishers, and a new breed of brokers [10, 15]. Even back-dated publications are possible if required to meet a deadline. Like the authorship in published papers, authorship on patents is also now available on payment. Another unwarranted

Table 2: *Global ranking of 16 Indian universities that have been red-flagged for very high Integrity Risk Index (RI^2) compared with an academically reputed institution (Control)*

Indian University	Rank by share in delisted journals	Rank by retraction rate	RI^2 Total score*	RI^2 world rank
1	2	4	0.838	1
2	3	3	0.807	2
3	14	1	0.772	3
4	9	2	0.761	4
5	6	5	0.702	5
6	1	30	0.675	6
7	5	14	0.590	7
8	13	10	0.551	9
9	27	8	0.528	11
10	37	9	0.486	12
11	7	51	0.483	13
12	8	72	0.438	17
13	25	19	0.414	20
14	56	13	0.416	21
15	52	15	0.382	27
16	45	32	0.342	37
17 Control	631	443	0.038	585

* **RI^2** = (Normalized Retraction Rate + Normalized Delisted Rate) / 2 [7]. Data for Indian universities are adapted from Table S12 of Meho [7] with identities of the universities suppressed (the serial numbers in column 1 here and those in Table 1 or Fig. 1 are not directly similar). The university # 17 is a control academic institution in India with high academic reputation.

consequence of the 'advantage' of being listed as an author in many papers or patents, is that the Heads of research groups and institutions often act as publication 'octopuses' seeking authorship in all publications of their subordinates irrespective of their being actually involved in the research. The subordinates have no choice but to comply since it is a question of their continuance in the job. Since the inter-institutional collaborations add to ranking points, authors with multiple institutional affiliations, which often change even in consecutive publications, have become common, as also the 'hyper-prolific' authors (publishing >40 papers per year). While this may reflect a genuine involvement in a few exceptional cases, in most instances the authorship and affiliations may have been sold, demanded or purchased. Since citation counts like h–index, self-citations and institution-level self-citations are also taken as a proxy for 'impact' of research, these metrics too have acquired notoriously unethical manipulations [2].

Currently two categories of journals exist. On one end of the spectrum of the money-driven publication market are journals with high Journal Impact Factors (JIF) that collect large sums from authors or their funding agencies as publication charges (article processing and/or open access charges), and let the authors feel 'elated' for publishing in these journals. On the other end are the paper mill journals that charge the desperate or unscrupulous authors for publishing anything to boost the quantitative scores. Unfortunately, the host institutions of such 'authors' are also tempted to promote these activities to secure higher institutional ranking and thereby make them attractive to prospective students and also eligible for prestigious institutional grants.

Thus, the present ecosystem of research publication market seems to encourage everyone to make money. The loser, however, is the sincere researcher who struggles to get enough funding to carry on the desired research work with due diligence.

c) Uncertain future of quality research in India

The establishment of many new and better-funded institutions of higher education (e.g., IISERS, IITs, NIITs, IIMs, AIIMS, central, state and private universities and research institutions) during the past two decades and consequent recruitment of young enthusiastic researchers have resulted in a marked improvement in the quality of research output from the country. However, with the quantitative parameters being used for assessments, the flourishing 'gray-market' research in India is eclipsing the genuinely bright 'spots'. As noted above, the increasing mis-conduct in Indian institutions has attracted intense scrutiny from national and international community of 'research sleuths'. *This has brought a wider disgrace that shadows the acclaim achieved by quality research contributions and technological achievements.* Unless curbed, the trajectory of research in India is on the verge of a wrong turn, with long-term, and possibly irretrievable, damaging consequence for academics and their credibility in the society.

Need for a national policy on 'Fair and Responsible Research Assessment'

Research is an essential component of higher education. Equally important is its role as a backbone for the progress in knowledge, which drives all-round societal advances through better understanding of nature and its forces, and more importantly, new technology-driven industry, agriculture and health-care systems. Research output has a cascading consequence since the new advances are built on the earlier known understanding. The cascading nature of increments in knowledge and

understanding require that to be reliable, all research output is based on ethical practices as well as scientific rigor at every level. Unreliable results of past can mislead the present and future researchers on wrong paths with damaging consequences, not only in terms of the time and resources wasted, but more importantly by derailing other researchers' sincere efforts due to the erroneous and misleading information in the literature. To avoid the long-term damaging consequences of unethically conducted research and the derivative research output, it is crucial that the country develops systems for 'fair and responsible research assessment' that promotes good quality research with scientific rigor, and replaces the current reliance on publication metrics that are prone to unethical entrancement [16].

Following extensive deliberation by its fellowship in 2018, INSA adopted a policy paper with comprehensive guidelines for dissemination and evaluation of research output in India [17]. A key highlight of the recommendations in this policy statement was that instead of assessing on *where was the research published*, the major issue for quality assessment must be *what the published research was*. The 2012 San-Francisco Declaration on Research Assessment (DORA, https://sfdora.org/) statement and the INSA guidelines clearly lay emphasis on quality over quantity. It is however, ironical that despite the DORA statement being signed by a large number of individuals and regulatory bodies in India, and the 2018 INSA guidelines being widely appreciated and followed by pronouncements on ethics in research by different agencies, a *sensu-stricto* implementation of these guiding principles is largely missing.

A demoralizing consequence of the continued use of quantitative parameter for assessment is evident in the institutional ranking system where established institutions with widely recognized credentials for their sustained quality of academic output get placed way behind much weaker counterparts that climb up through '*gaming' of the publication and citation counts*. Likewise, individual researchers with real impact-making research output find themselves at a disadvantage because of their 'poor' quantitative score.

Some suggestions for a national policy on 'Fair and Responsible Research Assessment'

Given the emergence of novel deceitful unethical practices and their increasing use in recent years, it is time that established academies, science-policy framing institutions, and younger researchers work together to formulate quality-based guidelines and introduce radical changes in the attitudes and processes used in assessments by the regulatory

agencies. Some suggestions that can act as 'primers' for developing more comprehensive policy document are noted below [16, 18].

a) Assessment of individual researchers

i) *The columns for Journal Impact Factor, 'National and International Journals' and other similar metrics must be removed from all assessment and grant application forms.*

ii) An individual's research output should be assessed on the quality and impact through an in-depth peer review of only 5-10 research papers and/or patents (identified by nominator/applicant along with notes on significance and use of each identified paper/patent) and the brief statement on the overall contributions of the applicant/nominee. The review should be by domain experts who do not have any conflict of interest.

iii) Assessment of quality of research outputs should cover:

   a) research articles in journals, irrespective of their inclusion in recognized commercial databases like SCOPUS and WoS,

   b) publications in alternative scholarly communication platforms (e.g., Publish-Review-Curate model/preprint servers such as arXiv, BioRxiv, etc),

   c) generation of datasets, softwares, null/negative studies, and

   d) scholastic activities like peer reviewing, editorship etc.

iv) Post-doctoral research carried out in India, which results in quality output, should be duly recognized. The current practice of preferring those with post-doc experience outside the country needs modulation so that due credit is provided to those who are trained in the country. This will help curb the 'brain-drain' while creating a skilled work force of post-doc researchers in India [19, 20]. The quality of training, research output and potential for independent research, should be the only issues for consideration.

v) Individuals with large number of publications and with concurrent multiple institutional affiliations be carefully scrutinized for veracity, and for their scholastic involvement in contributions. It may be mandated that each publication carries an explicit statement on contribution by each author.

vi) It should be the responsibility of corresponding author to ensure that the research output being communicated does not entail any misconduct. Retractions of any published paper by authors because of justifiable errors of omission, but not of commission, should be carefully evaluated and considered. However, in cases

where the retraction is initiated by the journal/publisher for any ethical misconduct, a more serious scrutiny and due penal action are warranted and all co-authors be held equally accountable.

b) Assessment of academic institutions

i) The NIRF and other international ranking parameters may be dispensed with since their current format has bred unhealthy practices. A wider discussion on the utility of such ranking systems is highly desired. If an institutional ranking system needs to be put in place, the academic ranking system must replace the current nearly completely quantitative parameter-based evaluation with parameters that truly recognize the quality of education and research output.

ii) Any unethical 'gaming' to influence ranking should be comprehensively checked and appropriately penalized by the institutional and central regulatory bodies.

iii) All the criteria for assessment of individuals as noted above, should also apply while assessing scholarly contributions of institutions.

iv) Assessment should also take into account extra-mural research funds generated by faculty through competitive grants and the actual intra-mural support provided by the institution to promote research. The latter should be assessed in terms of percentage of the total earnings of the institution through fees and other intra-mural sources during the period of review.

v) Statements about inter-disciplinary and inter-institutional collaborative research, and about 'Visiting faculty', need careful scrutiny to ensure that collaborations and authorship are genuine rather than being 'gamed'.

vi) Since the major activity of higher academic institutions is to impart knowledge and training of students to enable them to competently progress in their life, the career trajectories and feed-back of the institution's alumni should be important parameters in recognizing the quality of education imparted.

vii) Any act on part of the institution and its members that compromise 'Research Integrity' must face exemplary penalties.

c) Assessments by Academies for electing fellows and other recognitions

i) While electing new fellows and selecting for awards/recognitions, INSA's 2018 guidelines [17] and the points noted above for assessment of individuals should be followed. It is essential that conflicts of interests are carefully examined and rigorously followed at every level.

d) Supporting research project proposals by funding agencies

i) India's R&D spending must increase significantly beyond the nearly stagnant figure of ~0.6% of GDP (including GST) to facilitate (a) liberal support for infrastructure development at educational institutions, including schools, with special emphasis on development of classrooms and research laboratories, and (b) promotion of quality basic and meaningful applied research by individuals and larger teams. In order to achieve this, the Anusandhan National Research Foundation (ANRF) must continuously enhance and monitor its support for quality research. At the same time, industry and philanthropic institutions need to proactively come forward to partner with educational and research institutions and, thereby, promote quality education and basic as well as applied research. It is desirable that 30% of CSR be committed to ANRF with appropriate incentives.

ii) Inter-agency alignments between funding agencies, institutions, and policy makers are essential to ensure that academics are assessed through similar parameters across the agencies, and to avoid multiple fundings for the same basic ideas.

iii) There is a need to sensitize the research community (younger as well as senior researchers) on the merits of moving away from the journal metrics-dependent assessment.

iv) Evaluation of research projects for funding should be based primarily on assessment of quality and impact of research output from previous work and the quality of proposed work, without the use of JIF or other publications-based metrics for assessment. Research integrity history of each researcher proposed as PI or Co-I of a given research proposal must be carefully examined for any past unethical conduct. It is also essential that a detailed record of the reasons of acceptance or rejection of any research proposal be made and be shared with the PI.

Promoting and sustaining high quality open-access research journals from India

It is a sad commentary on our science fraternity and establishments that India has not been able to develop any research journal with global respectability. A few of the research journals published by the science academies in India or other agencies have been considered better than the numerous other research journals published from India. However, even these have not attracted a minimal fraction of quality research outputs from Indian researchers, especially from those associated with

better known research institutions or universities. While discussing why Indian research journals are not making a mark, Lakhotia [21] noted, "If established scientists in the country do not wish to publish even some of their research output in Indian journals, do not wish to seriously review manuscripts for these journals and, more importantly, directly or indirectly penalize, irrespective of the quality of work, those who publish in them, these journals would continue to struggle and fail to become internationally competitive. *Thus we are the enemy of established research journals published in India*." This scenario must change. Established researchers in the country need to lead in supporting good peer-reviewed journals published by academic societies in India through publication of some of their groups' best research outputs, and by being active peer-reviewers for these journals. That will not only help the journals attain the deserved academic prestige but will also generate confidence in younger researchers in journals published by Academies and other academic institutions in the country [21, 22].

The Academies should be in full control of their research journals, without any partnership with commercial publishers. It is necessary to dispassionately examine if the current partnering with commercial publishers has really improved the academic quality of these journals. The Academy journals should have a good editorial system that ensures a proper and timely peer-review and competent processing of submitted manuscripts so that, if accepted, the accepted version appears online within 10-20 weeks of initial submission. Fellows of the academies must be partners in improving these journals with passion since it is in the long-term interest of the country's academic fraternity. There is a strong need for synergy between the different academies to achieve this. They may also consolidate their thematic journals together for a better cumulative quality. The Academies, in concert with governmental agencies should develop good preprint servers co-existing with main journals.

Concluding remarks

Formulation of guidelines for responsible research assessment and implementing them are indeed challenging. However, it is also obvious that overhaul of the present quantitative metrics-based research assessment is critically essential to restoring and improving the sanctity and quality of country's academic and research environment.

INSA along with other academies needs to act as autonomous 'think-tanks' and advise government and public through timely 'white papers', status reports and policy-paths. It needs to be ensured that governmental funding of Academies does not affect their intellectual

autonomy. Any compromise in this will compromise robustness of the scientific firmament of India.

INSA, as a premier science academy in the country, needs to be proactive in promoting quality- rather than quantity-based assessment of research output at individual as well as institutional levels. It should initiate wider discussions with all stake-holders in a bottom-up manner and prepare well-documented 'white paper' on the *modus-operandi* for assessing individuals for recognition, for research grant approvals, and for assessing academic institutions. At the same time, it must make use of its status to ensure effective implementation of such guidelines. Finally, we must appreciate that a country and its well-being will be as good as its scientific fraternity is, how well it is empowered and how well the scholastic fraternity assumes its responsibilities.

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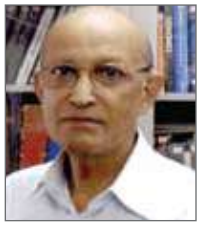

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neurodegeneration, tumour biology, Ayurvedic biology etc. In addition, he has been proactively involved in discussions on quality of higher education, research and publication ethics. Leading by example, Prof. Lakhotia is a strong votary of improving the quality of research journals published in India.

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His awards include, the National Geoscience Award for Excellence by Government of India, the Farouk El Baz Award for Desert Research by the Geological Society of America and Lifetime Achievement Award by the Indian Geophysical Union.

Let the STEM* Engine Run: Release the Brakes

N. Sathyamurthy

Scope

There is a general perception that the improvement in the quality of education and scientific research in India is not commensurate with the number of academic institutions and research and development laboratories that have emerged in recent times. It is becoming more and more difficult to pursue science, particularly if it requires state-of-the-art equipment. Indian institutions do not seem to count when it comes to global ranking. Having India's own ranking system does not seem to reflect the true state of the academic institutions in the country. Indian educational system does not seem to be producing employable graduates, with the result that the demographic dividend that India has may not translate into realizable benefits for the nation. It is against this background that this article tries to analyze what has been achieved so far, where the bottlenecks are and what needs to be done to keep the engine of growth in science, technology, engineering, and mathematics (STEM) moving. It was gratifying and reassuring to hear the Prime Minister of India declare in his first meeting of the Governing Board of Anusandhan National Research Foundation (ANRF) on September 10, 2024, "The scientific community of the country should have faith that there will be no dearth of resources for their endeavours".

India after independence

Soon after independence, India went about setting up research laboratories across the country through the Council of Scientific and Industrial Research (CSIR), Department of Atomic Energy (DAE, 1954) and the Defence Research and Development Organization (DRDO, 1958).

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*STEM: Science, Technology, Engineering and Mathematics

Although C.V. Raman (the only Indian Nobel Laureate to have won the Nobel Prize for science done in India) referred to them as Taj Mahals of Indian science, they played a critical role in developing science and technology in the country. Article 51-A (h) of the Constitution of India declares: "It shall be the duty of every citizen of India to develop the scientific temper, humanism, and the spirit of enquiry and reform".

India has come a long way in the last 75+ years after independence in school education and higher education and in terms of Research and Development (R&D) capability. A concept note circulated by the Department of Education recently suggests that about two thirds of our population is below the age of 35, there are 58,000 Higher Education Institutions catering to 43 million (48% female) students, and there are 6,000 R&D cells, 15,000 innovation councils, and 10,000 Atal tinkering laboratories. India stands the 4th highest in terms of Gross Domestic Product (GDP), next only to the United States of America, China, and Germany. According to Scopus, India ranks fourth in the order of number of research publications also, after China, USA, and UK. We have moved from the position of a ship-to-mouth country in the early 1960s to a country producing surplus food, thanks to the Green revolution. While China is the largest producer of food in the world, India comes next. We are the largest producer of milk, jute, and pulses. Green revolution was followed by White revolution (milk production) and Yellow revolution (oil seed production).

Science and technology capability

While being committed to the use of nuclear energy for peaceful purposes, India conducted two nuclear tests for geopolitical reasons: Pokhran I (Smiling Buddha, May 1974) and Pokhran II (May 11, 1998). Owing to the success of the latter, we celebrate May 11 as the Technology Day. The then Prime Minister declared: **Jai Vigyan**! Following the Pokhran tests, we had to suffer sanctions by the United States of America and other countries. The blessing in disguise was the push to become technologically self-reliant. While we reminisce with pride the image of Abdul Kalam carrying a sounding rocket on the back of a bicycle, we have every reason to be proud of India emerging as a space power. Chandrayaan-1 mission was successful, and it led to the detection of water for the first time on the dark side of the moon. Chandrayaan-3 achieved soft landing on the moon's south pole in 2023. Mangalyan (orbiting mission around Mars) demonstrated our capability for reaching scientific and technological (S&T) heights. I remember vividly the late Dr Kasturirangan describing the kind of accuracy it took to accomplish such a mission. The Aditya-L1 mission (2023) aims to study the Sun

from a vantage point. The launch of Astrosat, a multi-wavelength space observatory, is a testimony to India's S&T prowess. Our observation stations (Dakshin Gangotri, 1983 and others) in Antarctica make sure that we are not left behind in exploring the last frontier on earth.

India has been particularly successful in its mission mode approach, be it in atomic energy, space, or deep ocean. Whenever technology was denied to it by the West, it went about developing indigenous capabilities, such as in supercomputing. India produces the largest manpower in software industry. India trained engineers lead the most powerful software entities in the world (Sundar Pichai, Google; Satya Nadella, Microsoft; for example). Indian companies like INFOSYS, TCS and WIPRO are among the largest software service providers in the world.

Such a rise in S&T power does not come overnight. It has arisen from the conscious investment made by the Nation in educating its people, building schools, colleges, and universities. I remember attending an elementary school in a parikrama around a temple in a village in the Union Territory of Puducherry, attending a 1-room-5-class school in another village in Tamil Nādu and studying Pre-University in a newly founded Government Arts College functioning from an erstwhile district education office in Cuddalore, before entering the premises of Annamalai University. Needless to add, my grandchildren go to much better schools today.

Scholastic tradition

Takshashila (Taxila, 5th century BCE – 2nd century CE) and Nalanda (427 CE – 1200 CE) were the early universities in India, and they attracted scholars from all over the world. While the former was known to have had scholars like Charaka (Ayurvedic medicine) and Kautilya (Artha Sastra) on its faculty, Nalanda was known for a variety of studies, including Buddhism. It took several centuries before Calcutta, Madras and Bombay universities were established in 1857 by the British for training English speaking clerks to serve the empire. University of Allahabad was founded in 1887. At the suggestion of Swami Vivekananda, Jamsetji Tata founded the Indian Institute of Science in Bangalore in 1909. Banaras Hindu University (BHU) followed in 1916, thanks to the efforts of Pandit Madan Mohan Malviya, who understood, "The millions mired in poverty here can only get rid (of it) when science is used in their interest. Such maximum application of science is only possible when scientific knowledge is available to Indians in their own country". Aligarh Muslim University was founded in 1920. Visva-Bharati, established in 1921, was initially started as an Ashram school by Rabindranath Tagore as he believed in "Education that begins at the very root". It was converted into a Central

University and an institution of national importance in 1951. The Minakshi College of Tamil, Music, and Sanskrit, established by Raja Sir Annamalai Chettiar, was converted to Annamalai University on January 1, 1929. It was the first privately funded university in India.

Post-independence, University Grants Commission (UGC) was set up in 1956 and several colleges and universities came up all over the country. Also set up were the Indian Institutes of Technology (IITs) in Kharagpur, Kanpur, Delhi, Bombay and Madras. Those 5 IITs have been acclaimed for the quality of education imparted and the leaders they have produced. They received global attention through the 60 minutes program of CBS broadcasting of the United States of America. Admission to the IITs became so competitive that Narayana Murthy of INFOSYS said famously that his son could not get into an IIT; therefore, he sent him to Cornell! Coaching centres sprang up all over the country to train students to "crack" the Joint Entrance Examination (JEE). IIT Guwahati was set up as part of the Assam accord. The erstwhile University of Roorkee was converted into an IIT. Regional Engineering Colleges were converted into National Institutes of Technology (NITs). There was a mushroom growth of engineering colleges in the country to help realize the dream of students (pushed by their parents) to become software engineers. There was Silicon Valley in the US calling, and there was Indian Silicon Valley, Bangalore, calling. The result was that the aspirations of the middle class to move up the economic ladder were getting realized. The bonus was that girl students enrolled in large numbers and joined the workforce. Many poor families managed to send their children to engineering colleges, and the abject poverty started disappearing in some states. Private engineering colleges became an attractive business model. Since employment was (more or less) guaranteed at the end of 4 years of engineering education, the poor and the middle class found it worth investing in. The number of medical colleges also increased, but it was not sufficient to meet the demands of the students aspiring to become doctors. A large number started going to countries like China, Russia, Ukraine, Azerbaijan,.., previously not thought of. The number of students aspiring to become scientists did not see a proportional increase. Therefore, based on the recommendations of the Science Advisory Council of the Prime Minister of India, two Indian Institutes of Science Education and Research (IISERs) were set up, one in Pune and another in Kolkata in 2006. An IISER followed in Mohali in 2007, and two more IISERs were set up in Bhopal and Thiruvananthapuram in 2008. As part of the OBC expansion, 14 central universities and several IITs were set up soon thereafter. Two more IISERs came up, one in Berhampur and another in Tirupati. Today, we have an NIT and at

least one Central University in each state. Most of the states have an IIT, an Indian Institute of Management (IIM) and an All-India Institute of Medical Sciences (AIIMS) at present. But the growth has not been the same for all these new institutions. While the first 5 and the subsequent 2 IITs are still sought after, the rest of them are struggling hard to move up the ladder of excellence, largely due to a shortage of quality faculty. Something similar is true of the NITs, IIMs and AIIMSs. I am not even mentioning the newly set up central universities.

According to the All-India Survey of Higher Education (AISHE), 2021-22, India has 1162 Universities, of which 685 are government managed (Central Govt. 240, State Govt. 445) and the rest are privately managed. The Gross Enrolment Ratio (GER) for the 18-23 years age group stood at 28.4. PhD enrolment was 24.8% in engineering and technology, and 21.3% in science. The total number of faculty (teachers) was 15.98 lakh (56.6% male, 43.4% female). But the numbers do not reveal the true state of those institutions.

There are several aspects to the problem of lower academic excellence and lower student enrollment. These include a lack of persons of standing as heads of institutions, not appointing faculty and staff of quality and admission of students based on factors other than merit. Academic excellence comes with functional and financial autonomy of academic institutions. Although the Indian higher educational institutions have depended on the Centre or State for their finances, they enjoyed academic freedom for a long time. While Sir Ashutosh Mookerjee was legendary in appointing C.V. Raman without a PhD degree as Palit Professor in the University of Calcutta in British times, post-independence, legend has it that the Vice-Chancellor of the University of Madras did not go to meet the Chief Minister, let alone the ministers. Although Annamalai University was a private university, the vice-chancellors were men of standing like Sir C.P. Ramaswamy Iyer, V.S. Srinivasa Sastri, to name just two. I remember a vice-chancellor of BHU stating how much power he had as per the act and statutes of the university. When asked, a vice-chancellor of Delhi University conceded that he had enormous powers to act (for the University). In earlier years, the search cum selection committees would meet and recommend persons of standing for the post of the Vice-Chancellor (VC) of a university or the Director of an institute. The recommendations were accepted by the Chancellor of the University or the Visitor of IITs and IISERs, and announcements were made immediately thereafter. Once appointed, the Heads of institutions were given full academic freedom in appointing the faculty and making decisions for the institute. Homi Bhabha and Vikram Sarabhai could succeed in their missions because of the freedom they had in selecting

persons of competence. In recent years, C.N.R. Rao has demonstrated how institutions could be built or revived by selecting quality faculty.

Academic governance

In the university setup, the VC is the Chairman of the Executive Council (EC). A person of standing, often an industrialist of repute, is the Chairman of the Board of Governors (BOG) for the IITs and IISERs. The final authority lies with the EC or the BOG. Today, many appointments are questioned by the government, and qualifications for various academic posts are dictated by it. Whenever there is a deviation (for academic reasons), institutes are often asked to reverse the decision and recover the "arrears" for no fault of the candidate. That is not an environment in which excellence can thrive. The less said about the universities, the better it is. UGC dictates almost everything, and in the absence of compliance, funds are withheld. Insistence on uniformity is a sure way to ensure mediocrity.

In the institutions that I served, academic freedom was sacrosanct. The faculty taught what was to be taught, conducted the examinations, and awarded the grades. No questions were asked by the Director or the Academic Senate. I remember a Head of the department telling me to set the standards high and make the students rise rather than lowering the standards to suit the students, as there is no lower limit. Unfortunately, that is precisely what has happened in many academic institutions in the country. In the name of helping the weaker sections of society, instead of students rising to the standards set by the academic body, the standards are lowered to help them pass. In our times, getting a first-class degree was commendable. Today, students get 100/100 in many subjects in high school, with the result, subsequent admission to colleges becomes difficult for many students. Once the funds were allotted to an academic institution, the freedom of purchase rested with the institute bodies. The procedures were transparent, and there was never any question of impropriety. Trust used to be the word. Today, unfortunately, that is not the case. Heads of institutions are answerable under the Right to Information (RTI) Act, to the Comptroller and Auditor General (CAG) of India and sometimes to the Central Vigilance Commission (CVC) and the Central Bureau of Investigation (CBI). Many heads of institutions are afraid of taking decisions because of the three C's.

Enter IISERs

Here it is worth looking at the progress made by the first five IISERs. They were given clear goals to set up institutions of excellence with a

detailed project report (DPR) and an initial outlay of Rs. 500 crores for each IISER. The Board of Governors (BOG) of each IISER comprised men and women, who were the "Who is Who" of Indian science. In a record 10 years, IISERs became an academic brand. The faculty were chosen carefully based on merit and were given academic freedom and financial support to pursue their research interest. It is a myth that Raman made his discovery by making a hole in the dark window to let the sun's rays in. His laboratory in Calcutta was comparable to the best in Europe at that time. Professor C.N.R. Rao's laboratory in Bengaluru is comparable to some of the best in the world in his line of research. Investment in state-of-the-art equipment is a prerequisite for achieving excellence in science (and technology).

The initial Memorandum of Association (MOA) gave each IISER autonomy that was eroded after they were made into institutes of national importance by an Act of Parliament in 2012. Furthermore, IISERs were clubbed with the NITs for overall governance.

The unique selling point of the IISERs was that the undergraduate education included an introduction to research methodology and meaningful research before the students graduated. This was in addition to the teaching and research at the post-graduate level, like in any other academic institution. The approach was multi-disciplinary from day one.

Students at the IISERs were chosen based on merit, like ranking in JEE or the top 1% of any state or central board of higher secondary school examination. Kishore Vaigyanik Protsahan Yojana (KVPY) scholars were given direct admission. Introduction of INSPIRE Fellowship by the Department of Science and Technology, Government of India in 2008 was a game changer. It was provided to all the students admitted to the 5-year BS-MS dual degree programmes of the IISERs. This led to many female students taking admission into IISERs, and it also facilitated many boys and girls from weaker sections of the society, particularly from Bihar, Madhya Pradesh, Rajasthan, and Uttar Pradesh. Unfortunately, the KVPY has been discontinued in recent years and INSPIRE Fellowships have become restrictive.

Graduates from the IISERs have gone all over the world and many have stayed back in the country. They have taken up positions in academic as well as non-academic sectors. Particularly satisfying is the fact that many are pursuing science in India or elsewhere. The faculty in different IISERs have established themselves as leaders in their fields as reflected in quality publications and peer recognition in the form of Fellowships of National Science Academies and the like. Many of them have filed patents and are pursuing translational research. The investment in the IISERs

has yielded rich dividends in the form of quality manpower trained and the quality science produced. The IISERs have demonstrated what is possible in India if given autonomy and financial support.

Scholarship

I know what it means to get a scholarship for higher studies. My father was a state government employee and was transferred from place to place at irregular intervals. I (and my siblings) went to a nearby (government) school, and I came as a school topper in high school (grade XI). Then I went to a nearby Government Arts College for my Pre-University. Thanks to the award of the National Science Talent Search (NSTS) Scholarship administered by the National Council of Educational Research and Training (NCERT), New Delhi, I could join Annamalai University for my BSc and MSc studies. Many of my contemporaries, who received the NSTS scholarship, have emerged as leaders in science in the country and elsewhere, the most famous being Venki Ramakrishnan, who got the Nobel Prize in Chemistry for the year 2009. I am fond of introducing him as a physicist, who worked on a biology problem and got the Nobel Prize in chemistry. I must add here that he would not have succeeded in this country.

Due to the commercialization of education at all levels, quality education is getting out of reach for a large section of the population, despite the Right to Education Act. Often, parents are forced to spend a substantial portion of their income for the primary and secondary education of their wards. Many (state) government schools are in such a shape that the principal of a school told me that he would not put his children in that school. When it comes to college education, the choice is invariably between engineering and medicine. While engineering education is within reach for a large number, medical education is beyond reach for many students, particularly in the lower strata of society. Scholarship plays a critical role in facilitating students to pursue higher education, particularly if they are economically weak. When it comes to pursuing science, society at large does not encourage students to take up science as their career because of the limited number of opportunities for a secured career. Today, it is truly paradoxical that there are many qualified scientists looking for jobs in India, and at the same time, there are many positions lying vacant in government laboratories and academic institutions for inexplicable reasons.

Brain drain

The United States of America benefited immensely when it gave shelter to scientists escaping from the Hitler regime. They were responsible

for the success of the Manhattan Project and the victory of the Allies in the second World War. After the war, America made full use of their intellectual prowess and emerged as a Superpower. In later years (1990's), USA gave shelter to many scientists running away from the erstwhile Eastern Bloc. To keep the hi-tech industry going and to keep the wheels of the economy moving smoothly, America continues to invest and attract brains from all over the world. A Nobel Laureate once told me that he was a member of a committee to take stock of the status of mathematics in the United States and that the committee, after carefully considering the matter, concluded that the country was doing well, but it had to make sure that the influx of immigrants was not stopped. The success story of Silicon Valley and the power of Artificial Intelligence (AI) stand testimony to their efforts.

Ground reality

Indian efforts to promote science seem to be half-hearted at times. Many of us have benefitted from adequate financial support and maximum autonomy and minimum interference in achieving what we could in the last five decades. Despite the government of India assuring and reassuring financial support to the scientists in the country, the ground reality is far from satisfactory. Often approvals of research proposals and release of funds are delayed, sometimes for years. Scientists in administrative positions are seized of this situation. What is more disturbing is the recent trend of stopping the funds after March 31 and starting from zero balance on April 1 because of the Treasury Single Account (TSA). Inclusion of Goods and Services Tax (GST) reduces the science budget by 20%. There seem to be far too many restrictions on the purchase of scientific equipment in the name of "Make in India". While the Government e-Marketplace (GEM) is good for purchasing furniture and other items, it falls short of expectations when it comes to buying equipment. Although the government has relaxed the rules recently, it is not enough to make a difference. Once a project is approved, funds should be released in earnest and academic institutions should be allowed to follow a transparent procedure to spend it. India should learn and imbibe best practices in countries where science has thrived and is thriving.

In the switch from the earlier Science and Engineering Research Board (SERB) to the current Anusandhan National Research Foundation (ANRF), there has been a delay in call for proposals and approvals and release of funds. It would have been wiser to have had a seamless transition without any break in the funding and evaluation process. Hopefully, the wheels of change will pick up momentum soon. The requirement that 70% of funds for ANRF must come from industry is unrealistic, considering

our experience and the lack of trust of academia by the industry. The academia has shown time and again that they can rise to the occasion, as they demonstrated during the COVID times.

Many of us are worried about the steep decline in standards across the board. Drop in quality in primary education has led to drop in quality in secondary education, and that in turn has affected the tertiary education. Unless we get bright students trained today, there will be no bright faculty tomorrow, and there will be no bright students the day after. Our lives will be managed by not so competent people. Despite all our criticism of our education system (rote learning, straight jacketed, etc.), India has consistently produced many bright students. Some attribute this to the evolutionary process (survival of the fittest). India Today magazine (August 19, 2025) states that 7.6 lakh students from India studied abroad in 2024. Imagine the kind of money that has gone abroad. There are estimates showing that the amount is large enough to build several academic institutions in the country. Thanks to the current policy in the United States, many bright Indians in the US are willing to come back to India, provided they get commensurate jobs back home. We should do everything possible to attract them. Schemes like Ramanujan Fellowship, Ramalingaswami Fellowship, INSPIRE faculty Fellowship, etc. should be enlarged manifold and to the level envisaged. It seems that only about 10% of the 800 or so applicants were selected for Ramanujan Fellowship this year. The country can afford to spend much more to attract a larger number of non-resident Indians to return. **We need to provide them jobs**. That will be our investment in the future.

It does not matter which aspect of society we are talking about. Quality begets quality. Quality leadership will bring in quality faculty, which in turn will train quality students, and quality students will emerge as quality faculty. The wheel of this Dharma will keep rotating. Everything possible should be done to help students from weaker sections of society to emerge at the top, by educating them, by providing scholarships and providing myriad opportunities to excel in their choice of profession, but in the end, they must compete with the best. Keeping positions vacant by insisting that they are reserved for a certain section of society has been counterproductive. Unless students are graduating, where will the faculty come from? A simple estimate of the desired student/teacher ratio for higher educational institutions would reveal that about 50% of the faculty positions lie vacant in the country. More so in state universities. Guest faculty is no substitute for regular faculty. Money saved by not appointing regular faculty is a pittance when compared to other expenditures incurred by the government.

Ease of doing science

There is a lot of discussion about the National Education Policy (NEP-2020) and its implementation. I studied in Tamil medium schools until I went to college. I know how handicapped I was. Going to the USA for my doctoral studies enabled me to become a global citizen. I was asked once in a Pakistani TV interview why there was such a difference in development between India and Pakistan, which became independent at the same time. The only meaningful answer I could give was the medium of instruction (English). There is a lot of effort made in forcing students to learn in their mother tongue in government schools. This, unfortunately, means that the poor will remain poor. If India wants to continue on its path of progress, it has no choice except to continue with English as the medium of instruction.

I am happy (and amused) to see that NITI AAYOG has initiated a dialogue with the scientific community about the ease of doing R&D. When you look at American universities, for example, there are institutions like Harvard, MIT, Caltech, Stanford, etc., which are top ranking. Then many universities would come under the 2nd or 3rd tier. Regardless of the rung of the ladder they belong to, all of them are adequately equipped in terms of basic infrastructure. But in India, the difference in infrastructure between institutes can be as striking as that between a mountain and a mole hill. There is IISc, and there are IITs and IISERs, some central universities, and there are others. The difference between them was realized decades ago, and the Department of Science and Technology, Government of India, came up with the Funds for Infrastructure in Science and Technology (FIST). With the funds made available, all that could be done was to ensure that the less endowed institutions were assured of a certain minimum facility, like a UV-Vis spectrophotometer and an FT-IR spectrometer and some computing facility. A major overhaul of the infrastructure is needed across the board, on a war footing. Buildings need to be renovated, laboratories need to be made state-of-the-art, quality faculty need to be hired and supported for teaching and research. The cost involved is not astronomical; it would be within the budget of the nation, particularly if it is spread over five years. If this is done, there would be some hope of a revival of academic institutions in the country. If not, an entire generation would be lost and that would be difficult to recover from.

Outreach and training the trainers

People all over the world are conscious of their money (tax) being put to best use by their governments. Understandably, they would like to know what the academic institutions are doing with the funds given to

them. I remember the Open House organized in IIT Kanpur to celebrate its silver Jubilee year, bringing people in droves from all walks of life. I have witnessed busloads of students coming to IISER Mohali and walking through its corridors, and witnessing scientific experiments. Institutions must invite students in different age groups from all nearby schools to lab demonstrations and popular lectures to get them excited. Each one of them should be looked at as a potential student at the institute. Catch them young is the mantra.

Some of my colleagues at IIT Kanpur and I have gone to several colleges, thanks to the funding from the Indian Academy of Sciences, Bangalore. Our lectures were well attended. Invariably, some of the students from those colleges came knocking at the doors of IIT Kanpur for their higher studies. The three Science Academies of India have joined hands in promoting summer internships for students and teachers. Several students have spent their summers in my lab, and many of them got some research done that led to publication in prestigious journals. Never underestimate the capability of young people. They are keen to learn, and they come up with new ideas.

The barrier between colleges and well-endowed academic institutions must be broken. The teachers in colleges must have access to well-endowed laboratories. The science academies can play a larger role in facilitating it. Every year, the number of teacher candidates selected for summer research internship is too little to make a difference.

In this era of internet, information is available at the touch of a button. Therefore, initiatives like SWAYAM and NPTEL are laudable and must reach a larger number of students and teachers. National knowledge network (NKN) classrooms were set up with the idea of experts sharing their knowledge through e-classrooms. For some reason, they have not taken off the way they could have.

Global ranking for Indian academic institutions has remained a pipe dream. Introducing the National Institutional Ranking Framework (NIRF) has not served the purpose. The NIRF ranking published each year raises more questions than it answers.

Summary recommendations

1. Allocate adequate funds to improve the infrastructure of all academic and R&D institutions across the country. India must loosen its purse strings and break the barrier of 1% GDP for its R&D expenditure if it wants to be counted among developed nations. An increased expenditure on this count will yield rich dividends, increasing the GDP in return.

2. The government can give a clarion call to the alumni of the old universities to come forward and donate liberally, with the assurance that the money donated would be put to good use and that the government would not come in the way of their utilization.
3. Appoint persons of academic standing and probity as heads of institutions, be it academic or R&D, through Search cum Selection Committees. Many persons of stature do not apply for such posts.
4. Make those appointments without delay so that institutions do not suffer without duly appointed Heads. Additional charge does not work for premier institutions.
5. Appoint professional leaders as Chairpersons of Governing Bodies without delay. Institutions often suffer without empowered heads. The success of the IISERs in the initial years could be traced back to the outstanding leadership of the BOG Chairpersons.
6. Ensure functional autonomy to government funded institutions.
7. The recently adopted Treasury Single Account (TSA) is a challenge for many academic institutions; it needs the attention of the government for its repeal.
8. Make purchase procedures simple and allow institutions to follow the procedure approved by their governing bodies.
9. Keep the rules for appointment of academic staff as guidelines; academic excellence cannot be dictated by numbers. Once the teacher: student ratio is accepted for academic institutions, there should be no further controls on the recruitment process. Critical mass of qualified faculty is essential for academic excellence in any discipline.
10. Provide adequate funds for research in academic and R&D institutions. Developments in science and technology over the decades have been possible only because of adequate funding and timely release of funds.
11. Allow all academic and R&D institutions to fill ALL vacant posts with quality personnel. They are suffering from lack of manpower from COVID time onwards. The student: teacher ratio is already agreed upon by the Department of Education. Nothing can be more demoralizing than not getting a job for academically qualified and trained personnel. The time is ripe to attract Indian talent back to the country to make India richer.
12. It may be a good idea to have one portal that lists ALL academic and R&D positions in the country.

13. One Nation One Subscription (ONOS) is a step in the right direction; it needs to be broadened in scope so that a larger number of students and faculty, particularly from less endowed institutions, colleges and schools and medical fraternity can get access to the current literature. There is no reason why private universities cannot have access to those journals paid for by the Indian citizens under the ONOS scheme. This becomes particularly crucial because Sci-Hub is banned in India as of now.
14. Young people want prompt response when they apply for jobs or for funding. Institutions must have a mechanism to respond to ALL communications.
15. More funds should be allotted to INSPIRE and other scholarships. Scholarships and Fellowships of all categories must be decided on time and funds released in time as most of the recipients do not have the wherewithal to survive without those funds.

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Thematic Thoughts

The Evolving Landscape of Chemical Engineering in India

Aniruddha B. Pandit and M.M. Sharma

Scope

This article examines the historical development, achievements, and future directions of Chemical Science and Engineering, as well as the chemical industry in India. It discusses the field's unique academic and research-driven origins, the industrial growth that followed India's independence, and the expansion of domestic chemical manufacturing and research and development (R&D). The article also highlights the current global standing and economic significance of the Indian chemical sector, the impact of policy and sustainability efforts, and emerging priorities such as process intensification, green chemistry, and digital technologies that are shaping its future competitiveness. Additionally, it suggests that Chemical Science and Engineering will not only focus on chemical production but will also expand into areas such as utilizing living organisms, developing innovative materials, and broadening applications.

The historical roots and unique identity

Chemical Engineering (CE) holds a unique position among engineering disciplines, being the only one, intrinsically linked to chemistry. Its origins in India were deeply embedded in academia. Unlike other engineering branches that often began as diploma courses in institutions like Guindy College in Chennai or Roorkee, CE was established within universities, starting as a post-B.Sc. course. This academic foundation, exemplified by the initiative of Prof. H.L. Roy in Jadavpur, Kolkata, in the 1920s, and the establishment of the University Department of Chemical Technology in Mumbai in 1933, fostered a strong culture of research from the very beginning. Institutions like Andhra University and Madras University followed suit, further solidifying CE's academic and research-oriented

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identity. This early emphasis on research set it apart from its counterparts and laid the groundwork for future innovation.

The post-independence industrial boom

The period following India's Independence in 1947 saw a rapid growth in the chemical industry, driven by the needs of a developing nation. The burgeoning textile industry created a high demand for chemicals like caustic soda and dyes, giving birth to a robust chemical manufacturing sector. This initial phase was soon followed by a focus on fertilizers and explosives, essential for agricultural development and national security. The emphasis then shifted to Ethyl alcohol-based industries, which were later supplanted by the rise of petrochemicals. The availability of surplus naphtha spurred the large-scale production of polymers such as polyethylene, polystyrene, and PVC. The advent of synthetic fibers like viscose rayon and nylon, alongside the critical need to boost food grain production, brought fertilizers and agrochemicals into sharp focus. This era was characterized by the rapid growth of indigenous chemical industries and a corresponding boom in "in-house research", particularly in the dyes and agrochemicals sectors.

Achievements of the Indian chemical industry so far

The Indian chemical industry is a cornerstone of the nation's economy and has achieved significant global standing. It ranks as the sixth-largest producer of chemicals worldwide and the third-largest in Asia. The sector is highly diversified, encompassing over 80,000 commercial products, and its market size is currently valued at approximately $220 billion, with projections to reach $1 trillion by 2040.

A key achievement is its pivotal role in exports, with India being a major global supplier. It is the second-largest manufacturer and exporter of dyes and the fourth-largest producer of agrochemicals globally. The industry also stands as the third-largest consumer of polymers in the world. Its contribution to the national economy is substantial, accounting for approximately 7% of India's GDP and providing employment to over two million people.

The sector's growth is supported by government initiatives like the Production-Linked Incentive (PLI) Scheme and the establishment of Petroleum, Chemicals and Petrochemicals Investment Regions (PCPIRs). Furthermore, the industry is increasingly focused on sustainability and innovation, driven by collaborative R&D efforts and adoption of global standards like 'Responsible Care.' This robust foundation solidifies the Indian chemical industry's position as a major and responsible global manufacturing hub.

The Indian chemical industry has made significant technical advancements, particularly in indigenous process development, speciality chemicals, green chemistry, and the adoption of advanced digital technologies (Industry 4.0). A crucial area of emerging focus is Process Intensification (PI), which is vital for enhancing global competitiveness and sustainability.

Major technological achievements

Indigenous process development and self-reliance

Indian R&D institutions, notably the Council of Scientific and Industrial Research (CSIR) and its laboratories (like IICT, NCL, RRL, Jorhat), have been crucial in developing and commercializing local technologies, leading to self-sufficiency in several key areas.

IICT, NCL, RRL, Jorhat had done extensive work in petrochemicals and training of manpower for commercialization of these technologies:

Eco-Friendly Hydrazine Hydrate Production: CSIR-IICT developed and eco-friendly process for producing hydrazine hydrate, which was adopted by industry, helping India reduce its dependence on imports.

Speciality Chemical Process Scale-Up: Indian chemical companies have developed the technical and process competency to carry out complex, multi-step reactions at par with global peers, making the country a global hub for contract manufacturing, particularly in agrochemical intermediates and Active ingredients (AIs), mainly Pharmaceuticals (API's).

Petroleum Refining Technologies: PSUs like BPCL, HPCL and IOCL and NCL have developed indigenous technologies for their refineries, including indigenous development of a cost-effective Gasoline Sulphur Reduction Catalyst.

Catalyst development

PSU R&D: Companies like BPCL, HPCL (Hindustan Petroleum Corporation Limited), and IOCL (Indian Oil Corporation Limited) have dedicated R&D centers actively engaged in indigenous catalyst development and process technologies. IOCL, for instance, has developed and commissioned in-house technologies, such as the ZSM-5 and IV-IZOMaxCAT catalysts, in its refineries. BPCL's R&D has successfully commercialized products like a cost-effective Gasoline Sulphur Reduction Catalyst.

Successful Indigenous Catalysts: A prime example of this collaboration is the globally competitive catalyst "Thoxcat ES" for LPG sweetening, co-

developed by CSIR-IIP and BPCL. This catalyst has been commercialized in numerous Indian refineries and even exported.

Gasoline sulphur reduction catalyst

Catalytic cracking of naphtha to increase the yields of olefins. However, much more catalyst development work is needed in this area and also the Fischer-Tropsch catalyst development.

The petrochemical industry is witnessing significant advancements in catalytic processes, driven by the increasing demand for light olefins like ethylene and propylene, and the need for enhanced energy efficiency and reduced emissions. A key area of innovation is the catalytic cracking of naphtha and other feedstocks to maximize olefin production, offering an alternative to traditional, energy-intensive thermal steam cracking.

Recent breakthroughs centre on advanced catalyst design, primarily involving zeolites. Specifically, the incorporation of nanocrystalline ZSM-5 and the blending of ZSM-5 with traditional Fluid Catalytic Cracking (FCC) catalysts (like USY zeolite) have shown remarkable results. These catalysts possess optimized pore structures and tailored acidity, promoting the selective cracking of naphtha-range hydrocarbons directly into light olefins while suppressing undesirable side reactions that produce coke and dry gas.

Furthermore, the introduction of steam-assisted catalytic cracking has been explored, where steam alters the reaction environment, boosting olefin selectivity and improving catalyst stability by reducing coke formation. Novel materials like zirconia-titania based catalysts are also being studied, demonstrating high naphtha conversion and good olefin yields by tuning surface acidity.

It is a globally competitive, low-cost catalyst that has been successfully deployed in over ten Indian refineries (including those of BPCL, HPCL, IOCL, and RIL).

Impact: The catalyst is a "drop-in" solution, requiring no major modification to existing LPG sweetening units. It offers lower catalyst consumption and significant cost savings compared to imported alternatives, successfully breaking the monopoly of multinational suppliers and aligning with the "Make in India" initiative.

Another key area is IOCL's in-house technologies

indSelectG® Technology: Developed by IOCL-R&D, this is a selective hydrotreating technology with an in-house developed catalyst for the desulphurization of cracked gasoline. The key advantage is minimizing

the loss of Research Octane Number (RON) while achieving stringent BS-VI/Euro-VI sulfur specifications (<10 ppmw), a major challenge for refiners.

The in-house development of catalysts in India is a critical effort to achieve self-reliance in the petroleum and chemical sectors, involving major Public Sector Undertakings (PSUs) and leading research institutions.

Key contributors and collaborations

CSIR Laboratories: The Council of Scientific and Industrial Research (CSIR) labs, particularly CSIR-Indian Institute of Petroleum (IIP), are central to this work. CSIR-IIP has partnered extensively with PSUs like BPCL (Bharat Petroleum Corporation Limited) to successfully develop and commercialize catalysts.

This collaborative approach aims to develop competitive catalysts for various processes, including hydroprocessing of residues, desulphurization, and production of new-generation fuels, ensuring both technological advancement and foreign exchange savings for the nation.

Academic Institutions: Leading academic institutions like the IITs and others contribute to the fundamental and applied aspects of catalysis research, often collaborating with PSUs and CSIR labs on specific projects, sometimes supported by funding bodies like the Ministry of Petroleum & Natural Gas.

Gas Separation and Purification: Technologies like HP-HiGAS for gas separation and **H2 PSA** for hydrogen purification. The journey of catalysts has progressed from bulk materials and old formulations to achieving maximum atomic efficiency. The initial focus involved optimizing traditional solid catalysts. The next major leap was the development of nanocatalysts (nanomaterials or nanoparticles), which offered greater surface area and tunable properties, improving catalytic performance.

The latest frontier is Single-Atom Catalysts (SACs). SACs maximize the utilization of expensive metal resources by isolating individual metal atoms on a support. This design creates uniform and highly active sites, potentially enhancing both activity and selectivity, but stability against aggregation remains a key challenge for industrial application.

Green chemistry and sustainable technologies

The industry is proactively integrating sustainability into its technological roadmap.

Waste-to-Energy (Biogas): Development of the Anaerobic Gas Lift Reactor (AGR) technology by CSIR for the efficient generation of

biogas and biomanure from organic solid waste, supporting the circular economy.

Environmental Solutions*:* Development and commercialization of refinery chemicals to improve environmental performance, such as HP-Bio Activa, a microbial additive to improve refinery effluent characteristics.

Green Hydrogen and Renewable Energy*:* Major players are allocating capital expenditure to transition towards **decarbonisation** and exploring new pathways, including the use of clean hydrogen in chemical production.

Industry 4.0 and process intensification

The sector is rapidly adopting digital technologies and focusing on Process Intensification (PI) to boost efficiency and competitiveness.

Smart Manufacturing*:* Implementation of Industry 4.0 technologies, including Artificial Intelligence (AI), Internet of Things (IoT), Big Data, and robotics, to create intelligent and connected chemical plants.

Real-Time Monitoring and Optimization*:* Using connected intelligence and data analytics to track and manage processes in real-time, enabling proactive problem identification, reduced downtime, and lower energy/resource consumption.

Focus on Process Intensification (PI): PI is recognized as a key technological imperative for India's chemical industry to ensure global competitiveness for basic chemicals. This involves a paradigm shift in process and equipment design, such as:

Micro-reactors and Downsizing of Reactors: Implementing smaller, more efficient reactors to achieve better heat and mass transfer, leading to enhanced safety, higher yield, and superior product quality.

Continuous Processing: Shifting from traditional batch processing to continuous, streamlined operations to significantly improve process and chain efficiency, and reduce capital and operating expenses.

The transformation of education and research

The education and practice of chemical engineering have undergone massive transformations. The early use of the slide rule was completely replaced by the widespread application of computers, which also ushered in an era of automation in chemical industries. The introduction of

the Graduate Aptitude Test in Engineering (GATE) in the early 1980s marked a significant milestone, leading to a quantum leap in the quality of postgraduate and doctoral research. The establishment of the Indian Institutes of Technology (IITs), starting with IIT Kharagpur in the 1950s, followed by IIT's in Bombay, Madras, Delhi and Kanpur and thus brought sea change in engineering courses and IIT became a global brand. A noteworthy development in recent years is that older IITs now have more postgraduate students than undergraduate students. This trend has further enhanced the quality of undergraduate education, as it is supported by a strong research ecosystem.

The digital disruption and its aftermath

The advent of the computer age brought with it a marked change in student priorities. A significant number of students began to apply for computer science as their first choice, leading to a setback for core engineering branches, including chemical engineering. This trend, coupled with many engineering graduates opting for IITs and MBAs, has resulted in a shortage of highly talented students entering core manufacturing units. This talent drain has created a challenge for industries that rely on a skilled workforce to drive innovation and maintain competitiveness. Addressing this requires a concerted effort to highlight the dynamic and impactful nature of careers in core engineering sectors.

The field of chemical engineering, traditionally rooted in foundational principles of thermodynamics, transport phenomena, and reaction kinetics, is undergoing a profound transformation driven by the integration of artificial intelligence (AI). This is not just a computational tool, but a partner that enables unprecedented efficiency and innovation.

Computational Fluid Dynamics (CFD) is a powerful, indispensable tool in modern chemical engineering, fundamentally transforming how processes and equipment are designed, optimized, and operated. By employing numerical methods to solve the governing equations of fluid mechanics such as the Navier-Stokes equations-CFD provides a virtual laboratory for simulating complex fluid flow, heat transfer, and mass transfer phenomena. This capability has moved chemical engineering beyond traditional empirical and experimental methods, offering unprecedented insight into the intricate physical and chemical processes occurring within reactors, pipes, and other crucial equipment.

One of the most significant applications of CFD is in reactor design and optimization. Chemical reactors are the heart of many processes, and their efficiency is heavily dependent on factors like fluid mixing, residence time distribution, and temperature uniformity. CFD simulations allow engineers to visualize and analyse flow patterns, identify dead

zones where mixing is poor, and pinpoint hotspots that could lead to thermal runaway. This detailed information enables the design of new, more efficient reactors and the optimization of existing ones, ensuring higher yields and product quality. For example, CFD is routinely used to design bioreactors and to study multiphase flows in systems like bubble columns and fluidized beds.

Beyond design, CFD is also critical tool for process scale-up and safety analysis. Scaling up a chemical process from a lab-scale prototype to an industrial-scale plant is a notoriously difficult task, often introducing unforeseen challenges related to fluid dynamics. CFD helps mitigate this risk by accurately predicting how a system's performance will change with size, allowing engineers to identify and address potential issues before expensive physical prototypes are built. Furthermore, CFD simulations can be used to model the dispersion of toxic or flammable gases in a plant, helping engineers design effective ventilation systems and emergency plans to enhance worker and plant safety.

In conclusion, CFD has become an essential component of the chemical engineer's toolkit. It reduces the need for costly and time-consuming physical experiments, accelerates the development cycle, and provides comprehensive data that is impossible to obtain through traditional means. By offering a detailed view into the complex world of fluid behaviour, heat, and mass transfer, CFD empowers chemical engineers to create safer, more efficient, and more productive processes, pushing the boundaries of what is possible in the industry.

AI-driven analytics are revolutionizing process optimization, allowing for real-time adjustments to maximize yield and conserve resources. This predictive capability also extends to equipment maintenance, preventing costly failures and ensuring continuous production. In materials science, AI accelerates the discovery of new compounds by simulating properties and enabling "inverse design," a process that previously took years of trial and error. Beyond efficiency, AI enhances safety through dynamic risk assessment and improves sustainability by optimizing processes to reduce emissions and waste, guiding the industry towards greener practices.

Despite its immense promise, the increasing reliance on AI introduces critical ethical and operational considerations. Algorithmic bias, for instance, could lead to unsafe or suboptimal recommendations if training data is flawed or unrepresentative. There are also significant challenges related to data privacy and the intellectual property of AI-generated designs. A crucial aspect is the need for Explainable AI (XAI) to ensure that engineers can understand the logic used and followed by AI, and validate that logic for its corrections and mathematical rigour and integrity.

Modern innovations in core chemical engineering

Chemical engineering has witnessed dramatic changes, especially in core areas of operation. The field is being revolutionized by the miniaturization of processes, with micro-flow reactors gaining prominence. These reactors make hazardous processes safer and can substantially improve reaction rates and yields by improving the space-time uniformity. In separation technology, which constitutes a major part of investment in chemical plants, significant advances have been made. The traditional distillation column has been modernized with quality software, better internals including structural packings, and plates. Reactive distillation and Divided Wall Columns have become common, leading to reduced capital expenditure. In extraction, novel methods like supercritical extraction are now commercially employed for high-value products like fragrances and flavours.

The field of chemical engineering is fundamentally intertwined with hydrometallurgy, a discipline focused on extracting and recovering metals from ores and recycled materials using aqueous solutions. Unlike traditional pyrometallurgy, which relies on high-temperature processes, hydrometallurgy operates at lower temperatures, offering a more energy-efficient and often environmentally friendlier alternative. The expertise of chemical engineers is crucial for designing, optimizing, and controlling these intricate processes, ensuring they are both economically viable and sustainable.

At the heart of hydrometallurgical operations are a series of chemical and physical unit operations that chemical engineers must master. The initial stage, leaching, involves the selective dissolution of valuable metals from the ore. A chemical engineer designs the optimal conditions for this process, including the choice of solvent, temperature, pressure, and reaction kinetics, to maximize metal recovery while minimizing the dissolution of impurities. Following leaching, the resulting "pregnant leach solution" is purified through separation techniques such as solvent extraction, ion exchange, or precipitation. These steps, a core domain of chemical engineering, require meticulous control to ensure the purity of the target metal and the efficient recycling of reagents. There is need to develop technology for lithium recovery from lean ores.

The final stage, metal recovery, can be achieved through methods like electrowinning or chemical reduction. Chemical Engineers are responsible for designing the reactors, managing mass and energy balances, and implementing process control systems to maintain consistent production. Furthermore, they are at the forefront of innovation in the industry, developing more sustainable processes by focusing on reagent regeneration and waste minimization. The principles of chemical reaction engineering,

thermodynamics, and mass transfer are the foundational tools that allow chemical engineers to transform raw materials into valuable resources in a safe and efficient manner.

Separations based on adsorption have seen dramatic improvements with the advent of new adsorbents like zeolites, molecular sieve carbons, MOFs, and COFs. During the COVID-19 pandemic, this technology was critical one could see the impact of on-site enriched oxygen generation through Pressure Swing Adsorption (PSA). Membrane-based separations have also made a major impact, notably through Reverse Osmosis (RO) for converting sea and brackish water into potable water. These processes and systems in turn required articulate simulations for process optimization. The advances in material sciences have enabled some dramatic changes such as selective removal of ethane at 1 to 5% from ethylene rather than other way round through selective adsorption of ethylene. Extraction with reaction allowed valorisation of lean ores, starting with uranium. Internals in extraction columns and design procedures have seen major advances. Supercritical extraction is commercially employed even for fragrances and flavour as stated earlier.

Chromatographic separations have now become common and new chiral columns allow, at commercial level, resolution of racemates and SMBC has made an impact. A major advance is for solvent based Nano filtration, even for polar solvents, which allow molecules above mol. wt. of 250 to be retained making the separation facile, robust and with much lower energy consumption.

A particularly novel advance is the use of charged membranes to separate divalent ions from monovalent ions, which will soon be used commercially to extract lithium from ores and also where monovalent Lithium can be separated from divalent Mg ions. Crystallization remains a vital area, especially for Active Pharmaceutical Ingredients (APIs), where product quality in terms of particle size, bulk density, and polymorphs is critical.

Recent trends in chemical engineering

Chemical engineering, traditionally focused on the design and operation of large-scale industrial processes, has undergone a profound transformation. In the 21st century, driven by complex global challenges, the field has increasingly hybridized, systematically integrating its foundational principles with those of other scientific and engineering disciplines.

This evolution is not merely an expansion but a redefinition of the profession, creating powerful new specializations.

A primary example of this hybridization is the deep integration with the life sciences. This synergy has given rise to biochemical engineering and bioprocess design, where engineers apply their expertise in kinetics, thermodynamics, and fluid dynamics to a cellular level. This hybrid field is now essential for the large-scale production of biopharmaceuticals, such as monoclonal antibodies and insulin. Chemical engineers are critical in designing and optimizing bioreactors—the vessels where living organisms are cultivated—and in developing downstream processing methods to purify the final product from the complex mixture of the culture broth. This requires a deep understanding of protein chemistry, fluid dynamics, and mass transfer to ensure product quality and yield.

The intersection of chemical engineering and biotechnology represents a crucial and dynamic field that bridges scientific discovery with practical application. While biotechnology focuses on using living organisms and their components to develop products, it is the discipline of chemical engineering that provides the tools and principles to transform these biological breakthroughs from a laboratory curiosity into a scalable, safe, and commercially viable reality. Without the expertise of chemical engineers, the vast potential of biotechnology would remain largely untapped.

One of the primary roles of chemical engineering is the design and optimization of bioprocesses. This involves applying core engineering principles—such as fluid dynamics, heat transfer, and mass balance—to systems containing living cells or enzymes. For example, in the production of antibiotics or fermented foods, chemical engineers design and operate bioreactors (fermenters) to ensure ideal conditions for microbial growth and product yield. The agitation is responsible for controlling temperature, pH, and nutrient supply on a large scale, ensuring consistency and efficiency. Significant work on the effect of agitation has come from the Institute of Chemical Technology.

Furthermore, chemical engineers are vital in the downstream processing of bioproducts. Once a fermentation run is complete, the desired product (e.g., a therapeutic protein, an enzyme, or a biofuel) must be separated, purified, and formulated. This complex series of steps involves techniques like chromatography, filtration, and crystallization, all of which Chemical Engineers meticulously design and scale up to meet production demands while maintaining product purity and quality. Their work ensures that the final product is not only effective but also free of contaminants and economically feasible to produce.

Directed evolution represents a transformative approach in chemical engineering, applying the principles of natural selection to design and optimize enzymes and other biomolecules for industrial applications. This

method, a powerful alternative to traditional rational design, circumvents the need for a complete understanding of a protein's structure and function. Instead, it relies on an iterative, three-step cycle that mimics the evolutionary process, allowing for the rapid creation of novel biocatalysts with tailored properties.

The first step in this engineered evolution is creating genetic diversity through random mutagenesis, where errors are deliberately introduced into the target gene's DNA sequence. This process generates a vast library of protein variants. Next, a rigorous screening or selection system identifies the variants that exhibit the desired characteristics, such as enhanced catalytic activity, improved thermal stability, or resistance to harsh solvents. The selected genes are then amplified, serving as the template for the next round of mutation and selection. This continuous process of "survival of the fittest" in a laboratory setting allows engineers to quickly navigate a vast sequence space to find optimal solutions.

Computational methods in directed evolution

Computational methods are integrated into the DE workflow in several key ways:

Bioinformatics

Identify "Hotspots" for mutagenesis by analyzing existing protein data. Multiple Sequence Alignment (MSA), Coevolutionary Analysis.

Molecular modeling and simulation

Predict the impact of mutations on enzyme function, stability or substrate binding/specificity. This allows for a virtual prescreening of variants before they are synthesized in the lab.

Molecular Dynamics (MD) Simulations to study protein movement and dynamics; Quantum Mechanics (QM) Simulations for high-accuracy reaction energy/transition state calculations; Molecular Docking to assess substrate binding.

Machine learning (ML) & AI

Build sequence-function models from experimental data to predict the fitness (activity, stability) to create a "smart library".

Supervised ML (e.g., neural networks, Gaussian processes) to predict fitness; Unsupervised Learning.

De novo design

Design entirely new active sites or protein scaffolds capable of performing a desired biotransformation.

ROSETTA, ORBIT (software suites for protein design)

Computational resources used and needed

The computational resources required for these tasks are significant and often necessitate access to high-performance computing (HPC) infrastructure.

Central Processing Units (CPUs)

Role: CPU Cluster Management.

Need: Large Clusters of CPUs (hundred to thousands of cores) are needed to process large libraries of variants.

Graphics Processing Units (GPUs)

Role: Essential for highly demanding, parallel computations where individual task takes significant resources.

Need: High-end GPUs (tens to hundreds) are crucial for accelerating MD and training complex AI models.

Software and frameworks

Role: The specialized software and programming environments are as critical as the hardware, such as

i) **Modeling Software:** (Computer-Aided Directed Evolution of Enzymes)

ii) **Simulation Software:** Molecular Dynamics packages

Data storage and transfer

Role: Storing large datasets of protein sequences, structural models are needed for

Need: High-capacity storage solutions (e.g. petabytes) and high-speed network connections are necessary.

Directed evolution

Directed evolution is a powerful technique for engineering enzymes (biocatalysts) to perform biotransformations that are highly valuable in

industrial and pharmaceutical synthesis. This process involves iterative rounds of genetic diversification (mutagenesis), selection/ screening, and amplification to "evolve" a biocatalyst with desired traits, such as improved activity, stability or altered specificity.

Here are some key examples of biotransformations using directed evolution:

Pharmaceutical synthesis (Chiral Compounds)

Directed evolution has been highly successful in creating enzymes for the efficient, large-scale, and environmentally friendly synthesis of complex drug intermediates, particularly chiral molecules (molecules that exist as non-superimposable mirror images).

Sitagliptin Synthesis: A key example is the evolution of a transaminase enzyme to produce an intermediate for the anti-diabetes drug sitagliptin (Januvia). This has resulted in a more sustainable enzymatic route, resulting in stereoselective transaminase variant that creates the pure chiral amine intermediate, reducing waste.

Chiral Amine Production: Evolving imine reductases and transaminases to create various chiral amines (important motifs in many pharmaceuticals, agrochemicals, and fine chemicals) with high enantioselectivity (high enantiomeric excess).

Antibiotic Production: The large-scale use of a directed evolution-improved D-amino acid oxidase to catalyze the transformation cephalosporin C into-keto-adipyl-7-amunocephalosporinic acid for beta-lactam antibiotic synthesis.

New Molecule Development: India achieved the development and patenting of Renofluthrin, an indigenously created molecule to combat mosquitoes, showcasing local innovation in addressing public health challenges.

Industrial chemical production

Directed evolution is used to tailor enzymes for large-scale industrial processes, often requiring stability in harsh conditions (high temperature, organic solvents).

Acrylamide Production: The commercial, multi-thousand-ton per year production of acrylamide (used in plastics) uses a nitrile hydratase enzyme, which has been optimized for industrial conditions.

Improved Enzyme Stability: Enzymes used in detergents and various industrial applications, such as subtilisin E (a protease), have been

evolved to display significantly increased thermostability (upto 65^{0}C) and enhanced activity in non-native environments like organic solvents.

Altering Substrate Specificity: Evolving enzymes to work on non-natural substrates. For example, a *Pseudomonas aeruginosa* lipase was evolved to significantly increase its enantioselectivity (E factor 1.04 to 25) towards a non-natural substrate, 2-methyldecanoate.

Creating novel reactivity

A more advanced application is evolving an enzyme to catalyze a reaction that is not known to occur in nature, or one that is typically only possible with chemical catalysts.

Non-Natural Amination Reactions: Evolution of a cytochromeP450 enzyme to perform a tricky, non-natural amination reaction replacing a precious metal catalyst (like rhodium, ruthenium or iridium) in industrial settings.

The introduction of Designed Enzymatic Biomaterial (DEB) Technology marks a significant breakthrough, offering solution for the synthesis of various materials that does not compromise on quality or functionality.

Computational methods are essential in modern directed evolution (DE) of enzymes for biotransformations, as they transform the traditional trial-and-error process into a more rational and efficient search for improved enzyme variants. By performing *in silico* screening before experimental work, these methods drastically reduce the experimental burden, saving time and laboratory resources.

The impact of directed evolution on chemical engineering is profound. In biopharmaceuticals, for example, it has been used to engineer therapeutic antibodies with improved binding affinity or to create enzymes for the more efficient and scalable synthesis of complex drug molecules. For biofuels, directed evolution has been crucial in developing enzymes, such as cellulases, that can efficiently break down tough plant biomass into fermentable sugars. This advancement makes the production of ethanol and other biofuels more economically viable and environmentally friendly. From creating detergents that work in cold water to developing enzymes that can break down plastics, directed evolution provides a versatile toolkit for solving complex industrial challenges. As the field continues to advance, integrating computational tools and robotics will further accelerate the discovery of biomolecules with unprecedented capabilities, solidifying directed evolution's role as a cornerstone of modern bioengineering.

Waste to wealth: Waste as a new resource

The concept of converting waste by-products into useful chemicals in Active Pharmaceutical Ingredient (API) manufacturing is a key part of Green Chemistry and the Circular Economy principles, often called waste valorization or chemical upcycling.

There is a need to valorize red mud from Aluminum refineries and valuable components from Phospho gypsum. Even fly ash from coal burning should be valorized apart from use in cement, eg. can we make zeolites for detergents and isolate cenospheres?

Here are some examples of this approach

Recovery and repurposing of solvents

Solvents typically make up the largest mass fraction of waste in API manufacturing. Instead of disposal, they are often converted back into a reusable resource using multiple separation and other recovery methods such as distillation, adsorption, etc. to remove unwanted impurities.

Recovery of chemicals from waste streams materials: The manufacturers of API 'Materials' Pharma Industries and Recovery of solvents used extensively in Pharma Industry.

Recovery of Unreacted/Expired Active Pharmaceutical Ingredients (APIs)

While not a direct synthesis by-product, a major waste stream (in the proportion of 1:50 of useful and wastes) in the broader pharmaceutical sector is unused or expired finished drug products. The valuable API itself can be recovered and repurposed.

Extraction and Recrystallization: The API (e.g., ibuprofen, acetaminophen, or gabapentin) is selectively extracted from the tablet or capsule excipients (binders, fillers, etc.) using safe solvents, followed by filtration and recrystallization to obtain the pure API.

Use: The recovered, high-purity API can be re-formulated into new drug products or used as a starting material for synthesizing new derivatives or compounds in chemical research. For example, recovered gabapentin and pregabalin have been chemically transformed into new, potentially bioactive compounds (e.g., azaspirocycle compounds).

Transformation of organic waste into feedstocks or materials

Research is exploring methods to break down process by-products and turn them into new chemical building blocks.

Artificial Photosynthesis for Organic Waste: Researchers have developed techniques that use sunlight, water, and photocatalysts to transform waste organic compounds into valuable alcohol and ether products. For instance, a common solvent by-product, acetonitrile, can be converted into useful chemical products using this method, simultaneously generating "green" hydrogen as an energy co-product.

Conversion to Carbon Materials: Through processes like pyrolysis (thermal conversion), drug waste and other organic process residues can be converted into biochar or activated carbon.

Use: These carbon-based materials can be used for water purification (to remove heavy metals and pollutants) or as precursors for synthesizing carbon-based nanomaterials (like carbon nanotubes or graphene) for various applications.

Metal catalyst recovery

Many API syntheses use expensive, rare, and often toxic metal catalysts (like palladium, platinum, or rhodium). Waste streams containing these metals are not discarded.

Precious Metal Reclamation: Catalysts are recovered from reaction mixtures and waste residue. They are then subjected to chemical processing to reclaim the pure metal, which is then used to prepare fresh batches of the catalyst. This is both an environmental and economic necessity.

The recovery of Cobalt, Nickel and Lithium from spent lithium-ion batteries is vital for sustainability. The three main methods are Pyrometallurgy, Hydrometallurgy, and Direct Recycling (or direct cathode reuse).

Recent development now are focussing on recovering specific metals using either Deep Eutectic solvents and ionic liquids or charge specific membranes.

Biological and chemical treatment of wastewater

While primarily for pollution control, some wastewater treatments can yield useful outputs.

Hydrogen and Oxygen Generation: Innovative strategies, such as using photocatalysts in wastewater treatment, can degrade hazardous compounds while simultaneously generating valuable by-products like hydrogen (H_2) and oxygen (O_2). The hydrogen, in particular, is a clean energy source.

Energy Generation: In lab-scale systems, microbial fuel cells (MFCs) have been shown to degrade hazardous compounds in pharmaceutical wastewater and simultaneously generate electricity.

Many advanced oxidation processes such as wet-air oxidation sonication, cavitation have been used to treat and minimize bio-refectory pollutants.

Harvesting water from flue gases—the hot exhaust gases from industrial processes like power plants and incinerators—is an emerging practice focused on resource recovery and energy efficiency. These gases contain significant amounts of water vapor as a byproduct of combustion, which can be condensed and collected.

Similar methods along with smart absorbents are used to convert water vapour into potable water in descent type environment.

The primary challenge and goal is to cool the flue gas below the dew point of the water vapor, causing it to condense into liquid water. This process simultaneously recovers the latent heat of condensation, improving overall system energy efficiency.

Key technologies used include:

Condensing Heat Exchangers (Economizers): These devices lower the flue gas temperature, often below the water vapor's dew point, allowing the steam to condense on the heat exchanger surface. The recovered heat is then typically used to preheat boiler feedwater or district heating water, while the condensate is collected. This approach is central to condensing boiler technology.

Deep-Condensation Systems with Heat Pumps: These advanced systems use absorption heat pumps to cool the flue gas to even lower temperatures (e.g., around 40°C), maximizing condensation and heat recovery. The recovered low-grade heat is then upgraded by the heat pump for more useful applications.

Desiccant and membrane technologies

Liquid Desiccant-Based Systems use a hygroscopic liquid (like calcium chloride solution) to absorb water vapor from the flue gas. The desiccant is then regenerated (water is released) using low-grade waste heat.

Organosilica Membranes are being researched to selectively separate water vapor (steam) from the flue gas, allowing for simultaneous water and latent heat recovery, potentially making plants water-self-reliant.

The practice offers dual benefits:

Water Conservation: It provides a new, non-traditional water source that can be recycled for in-plant use (e.g., cooling, boiler feed) or, with proper purification, for external consumption.

Energy Recovery: It significantly improves the thermal efficiency of the industrial process by recovering latent heat that would otherwise be lost up the stack, leading to fuel savings.

However, challenges include:

Corrosion: Flue gases contain acidic components (like sulphur dioxide SO_2), that react with condensed water to form corrosive acids requiring expensive MOC.

Water Purity: The collected condensate is often acidic and contains dissolved pollutants, requiring subsequent treatment before it can be used.

Cost: The capital cost of installing specialized heat exchangers, pumps, and purification equipment can be substantial.

Chemical Engineering forays in Renewable Materials: Biomass is a renewable resource and with Global warming due to CO_2 emissions from burning of fossil fuels and pressure on chemical industry to aim for carbon neutrality and "Act zero", the attention has been shifted to Renewable resources and process developments having least environmental impact.

This has resulted into concepts such as "Bio-refinery" with biomass as a waste feed stock to use it as fuels to convert them into chemicals.

Lignin is the planet's second most abundant biopolymer, a complex, three-dimensional aromatic polymer found in plant cell walls. Traditionally, it's a largely underutilized byproduct of the pulp and paper industry, often just burned for energy. A major distributed source is sugarcane bagasse. However, its aromatic structure makes it an invaluable renewable source for a host of industrial products—a process known as lignin valorization.

The industrial value derived from lignin can be categorized into polymers, composites, and fine chemicals.

Polymers and materials

Phenolic Resins (replacing petroleum-based phenol in adhesives for wood products), Polyurethanes, and Epoxies (as partial replacements for

fossil-based polyols). Lignin is also being used to create Carbon Fibers for lightweight, high-strength materials, and as a component in 3D-printing composites.

Fine and platform chemicals

Vanillin (an aroma chemical), and various Aromatic Monomers and Phenolic Compounds like guaiacol and syringol, which are crucial building blocks for other speciality chemicals. This is achieved through depolymerization processes.

Other applications

Lignosulfonates (byproducts of the sulfite pulping process) are widely used as dispersants and surfactants in cement additives, drilling fluids, and as binders. Lignin also serves as a natural antioxidant and UV protectant in coatings and plastics.

The move towards a sustainable, bio-based economy hinges on utilizing resources like lignin. Chemical knowledge is essential for developing the sophisticated catalytic, biocatalytic, and separation techniques necessary to efficiently break down and functionalize lignin's complex structure into these valuable, marketable commodities.

The utilization of algae as biomass represents a significant frontier in the quest for sustainable energy and resource management. Algae, particularly fast-growing microalgae, possess numerous advantages over conventional energy crops. They exhibit remarkable photosynthetic efficiency and can be cultivated in non-arable land and even in wastewater, thereby avoiding competition with food crops and aiding in water remediation. Furthermore, their rapid reproduction rate allows for frequent harvesting and higher biomass yield per area compared to terrestrial plants.

Algae biomass is a versatile feedstock, rich in lipids, carbohydrates, and proteins, which can be converted into a diverse array of valuable products. The high lipid content of some microalgae strains makes them ideal for producing biodiesel through transesterification. The carbohydrate-rich species can be fermented to yield bioethanol, and the entire biomass can be subjected to anaerobic digestion for biogas (methane) or thermochemical processes like pyrolysis for crude bio-oil. Critically, algae consume atmospheric or industrial CO_2 during growth, making the resulting biofuels potentially carbon-neutral.

Despite their potential, challenges in mass production persist. High costs associated with cultivation, particularly in closed photobioreactors,

and the energy-intensive processes of harvesting, drying, and oil extraction currently hinder large-scale commercialization. Research is focused on developing cost-effective techniques, such as integrated systems that couple algal cultivation with industrial flue gas capture or wastewater treatment, to enhance economic viability and fully realize algae's promise as a sustainable, third-generation biofuel source.

Emerging environment friendly techniques

Dilute nitric acid acts as an oxidant, often requiring heat and/or pressure to drive the reaction. A key feature of its redox reaction is the reduction of the nitrogen atom from the +5 oxidation state into various lower states, primarily nitric oxide or nitrogen dioxide, which are often observed as brown fumes (nitrogen oxides).

Dilute nitric acid is commonly used for the oxidation of:

Alkyl side chains of aromatic compounds

Dilute HNO_3 can oxidize alkyl groups attached to an aromatic ring, especially under elevated temperature and pressure, to form carboxylic acids. The oxidation typically targets the benzylic (alpha) carbon.

Substrates: Toluene and its substituted derivatives.

Product: The side chain is oxidized completely to a carboxylic acid (COOH) group. For toluene, the product is benzoic acid.

Alcohols to carboxylic acids

Benzylic alcohols can be selectively oxidized to aldehydes from Nac10 and TEMPO.

Primary Alcohols: Oxidize to carboxylic acids.

Secondary Alcohols): Oxidize to ketones.

Carbohydrates (Sugars)

Nitric acid is a classic reagent for oxidizing sugars, such as D-glucose.

Reaction: Oxidation of both the aldehyde group and the primary alcohol group in aldoses to carboxylic yields a dicarboxylic acid known as an aldaric acid.

Example: Oxidation of D-glucose yields D-glucaric acid.

These methods with dilute HNO_3, result into reduced gaseous emissions and lower subsequent treatment/recovery cost

Simultaneously, chemical engineering has converged with materials science and nanotechnology. This collaboration enables the precise manipulation of matter at the molecular scale to create advanced materials with tailored properties. This includes the development of smart polymers that respond to external stimuli, advanced semiconductors for faster electronics, and lightweight composites for aerospace and automotive applications. The role of the chemical engineer in this process is to design the synthesis pathways for these new materials, control reaction conditions, and scale up production from the lab to commercial viability. This cross-disciplinary approach is vital for developing the building blocks of future technologies.

A paradigm shift: Distributed electrochemical manufacturing

The chemical industry is undergoing a critical shift towards decarbonisation and sustainability, with electrochemical processes powered by renewable energy (like solar and wind) emerging as a transformative pathways. This approach enables distributed manufacturing, moving away from massive, centralized petrochemical plants.

Electrosynthesis uses electrons as clean reagents, often allowing reactions to occur under milder, ambient conditions, which enhances energy efficiency and significantly reduces hazardous waste compared to conventional thermochemical routes. Critically, electrochemical reactors are inherently modular. This modularity minimizes the economics of scale typically required for large chemical facilities, making smaller, decentralized plants viable. Distributed facilities can be strategically placed closer to both feedstock sources (like local biomass or captured CO_2) and end–users. This proximity drastically cuts transportation costs and logistical complexity for low-density feedstocks (like agricultural waste) or hazardous products.

Key examples already being explored for distributed electrochemical production include green hydrogen (H_2), ammonia (NH_3), and the conversion of biomass-derived compounds into valuable chemicals leading to adipic acid. By leveraging local renewable power and reducing supply chain risk, distributed electro synthesis is poised to redefine chemical production for a greener, more resilient future.

The Chemical Engineers have played a variety of roles over the years and have contributed in the following areas:

Role of chemical engineers in polymer synthesis and it's application

Polymer advances and fluidized bed polymerization (FBRs)

Advances in Polymer Science are driven by the need for enhanced functionality and sustainability. Innovations include developing specialized polymers with improved mechanical, optical, or biocompatible properties for advanced applications like microfluidics. Crucially, sophisticated Computational Fluid Dynamics (CFD) and kinetic models have become vital tools for predicting and optimizing polymer molecular properties and reactor performance.

The Fluidized Bed Reactor (FBR) is the leading technology for high-volume polymer synthesis, particularly polyolefins. Its core advantage lies in its fluid-like state, which ensures excellent heat transfer—vital for removing the intense heat of the exothermic polymerization reaction. This prevents hot spots that cause polymer particles to melt and agglomerate, leading to efficient, continuous production.

Recent technological advancements in FBRs focus on maximizing productivity, primarily through Condensing Mode Operation (or Super-Condensing Mode). In this process, a portion of the recycle gas stream is cooled below its dew point in an external heat exchanger, creating a two-phase mixture of gas and liquid (called Induced Condensing Agents or ICAs). This liquid is then injected back into the reactor. The rapid evaporation of this liquid inside the bed provides massive additional cooling capacity (latent heat of vaporization), dramatically increasing the rate at which the heat of reaction can be removed, and thus boosting polymer production capacity.

Key polymers produced using FBRs include

Polyethylene (PE), such as High-Density (HDPE) and Linear Low-Density (LLDPE) and Polypropylene (PP).

Chemical engineers are instrumental in developing and integrating additives, which are crucial for both polymer processing and final application performance. Additives are speciality chemicals incorporated in small amounts to enhance or modify the material's properties. During processing (like extrusion or injection molding), Process Aids such as lubricants and fluoropolymer-based compounds are used to improve melt flow, reduce friction against machinery, and prevent defects like melt fracture. This optimization increases production efficiency, lowers energy consumption, and improves the final product's surface quality.

For application performance, chemical engineers formulate functional additives like flame retardants (for safety in electronics/construction), UV stabilizers/antioxidants (to prevent degradation and discoloration from sunlight and heat, prolonging service life), and plasticizers (to increase flexibility in products like PVC tubing). The precise development and compounding of these additives ensure that the synthesized polymers can meet stringent industry specifications for a vast array of high-performance applications.

Chemical engineering contribution in advanced material synthesis

The role of Chemical Engineers in the synthesis of advanced materials like MOX (Mixed Oxide Fuel), HMOG (High-Mobility Organic Semiconductors), and MOF (Metal-Organic Frameworks) is crucial, focusing on process development and scale-up.

Chemical engineers translate laboratory-scale material synthesis methods (like solvothermal, electrochemical, or mechanochemical for MOFs) into economically viable and safe industrial processes. Their key contributions include:

- Process Design and Optimization: Selecting and optimizing reaction conditions (temperature, pressure, solvent, mixing) and unit operations to control material properties (e.g., crystallinity, particle size, morphology, and purity).
- Reaction Engineering: Designing the optimal reactors for the specific synthesis (e.g., batch, continuous, or flow reactors) to ensure efficient mixing, heat transfer, and product consistency.
- Scale-up and Manufacturing: Addressing challenges associated with mass production, such as cost reduction (raw materials and energy), process stability, and waste management to transition the material from a research product to a commercial one.
- Safety and Environmental Compliance: Implementing safe operating procedures and designing processes that minimize environmental impact and comply with regulations.

This engineering expertise ensures that these sophisticated materials can be reliably and affordably produced for applications such as nuclear energy (MOX), advanced electronics (HMOG), and gas storage/separation (MOF).

Furthermore, the discipline has absorbed concepts from computer science and environmental science. The use of artificial intelligence and machine learning now allows for the optimization and control

of complex reaction systems and manufacturing plants. Meanwhile, the focus on sustainability has intertwined chemical engineering with environmental science, promoting green chemistry and the development of renewable energy systems. This hybridization of core principles is essential for addressing the world's most pressing issues, from global health to sustainable energy.

In conclusion, chemical engineering is the essential link that translates biological innovation into industrial production. By providing the expertise in process design, scale-up, and purification, chemical engineers enable the mass production of biopharmaceuticals, biofuels, and countless other biotechnological products. They are the problem-solvers who ensure that groundbreaking research can have a tangible and positive impact on society.

Thus, one can see from the above discussion, history and current capabilities Chemical Engineering appears to be the most versatile branch of Engineering profession, capable of adapting and modulating its requirements using the principles of Material and Energy Balance (a subject Unique to Chemical Engineering course), transport phenomena, thermodynamics (limiting transformations) and kinetics (rate processes) utilizing, newer and modern materials, AI, optimization (sustainability) and contract (safety) process applicable for non-living and living systems.

This is truly a sustainable branch of engineering taking various "Avatars" every few decades in line with the every changing need of Human Society.

Peek in future

Looking further ahead, we can speculate about future "avatars" of chemical engineering that could be truly game-changing breakthroughs — the kind we can barely imagine today. Here are some possibilities: as suggested by AI (courtesy Dr. R.A. Mashelkar).

Quantum chemical engineering

What it could be: A discipline where chemical processes are designed and controlled at the quantum level.

Game-changing aspect: Harnessing quantum computing + quantum chemistry to simulate, predict, and even steer reactions in real-time with atom-by-atom precision.

Impact: New drugs, materials, and catalysts designed *in silico* with zero trial-and-error, leading to a near elimination of lab-scale experimentation.

Programmable matter engineering

Chemical engineers would design matter that can change its properties dynamically — self-healing, shape-shifting, tunable conductivity or permeability, rather than just chemicals or polymers.

Using molecular switches, supramolecular chemistry, and adaptive polymers to make materials that reconfigure themselves on demand.

Carbon-negative earth systems engineering

Beyond carbon capture, engineers design planetary-scale chemical processes that actively restore Earth's balance — scrubbing greenhouse gases, regenerating soils, even fixing ocean acidification.

A perfect fusion of chemical, biological, and geo-engineering to run "synthetic metabolisms" for the planet, leading to Human-driven "climate repair industry," with chemical engineers as custodians of planetary health.

Synthetic life process engineering

Chemical engineering converging with synthetic biology to create engineered organisms or protocells that act as factories, sensors, or healers, resulting in living materials for construction, bacteria that clean up plastics and heavy metals autonomously, or even artificial cells that act as nanomedicine inside humans leading the next phase of evolution.

Astrochemical engineering

Engineering chemical systems that function outside Earth — on Mars, the Moon, asteroids, or in deep space aiming for Resource extraction from extraterrestrial bodies, chemical synthesis under microgravity and radiation, closed-loop life-support chemistries, with chemical engineers as the "terraformers" of other worlds.

Conscious materials and neuro-chemical engineering

What it could be: Design of materials and devices that interact directly with the human nervous system at the molecular level development of neural–chemical interfaces that allow matter to "sense" and respond to emotions, thoughts, or intentions. The expected outcome is prosthetics that feel like natural limbs, emotion-responsive environments, or even chemical and diabetic platforms for human–AI driven robotics assisting human's bodily movements in walking, climbing, running etc.

Energy alchemy engineering

A future branch dedicated to direct matter–energy transformations far beyond combustion or batteries — possibly harvesting energy from vacuum fluctuations, nuclear waste conversion, or exotic fuels.

Moving from "energy carriers" (like fuels, hydrogen, batteries) to direct conversion methods. This may lead to radical energy abundance, decentralization of power grids, and solutions to the world's energy crisis.

In summary

Chemical engineering's future avatars might not just be about "manufacturing chemicals" but about engineering life, matter, and even planetary systems themselves. The field could move from factories to living organisms, intelligent materials, and cosmic frontiers.

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M.M. SHARMA is the past President of the Indian National Science Academy (INSA). He obtained a Bachelor's and Master's degree from the University Department of Chemical Technology (UDCT), now known as the Institute of Chemical Technology (ICT), and received his PhD in Chemical Engineering from Cambridge University, United Kingdom. In 1964, he returned to India to serve as a Professor at the University of Bombay and subsequently became the Director of the University Department of Chemical Technology (UDCT), which is now called ICT, a Deemed University. Professor Sharma has made pioneering contributions to the fields of chemical engineering science and technology. He has served in the petroleum and natural gas sector as Chairman of the Scientific Advisory Committee (SAC) and in the SAC to the Cabinet and Prime Minister. He has been honoured by numerous academic institutions, including the Indian Institutes of Technology (IITs), through honorary doctorates. His accolades include the Leverhulme Medal from the Royal Society, the S.S. Bhatnagar Prize in Engineering Sciences (1973), the FICCI Award (1981), the Vishwakarma Medal from the Indian National Science Academy (1985), the G.M. Modi Award (1991), and the Meghnad Saha Medal (1994), among others. In 1990, Professor Sharma became the first Indian engineer to be elected as a Fellow of the Royal Society, London. He is also a Fellow of the Indian Academy of Sciences, Bangalore; the Indian National Science Academy, Delhi; an Honorary Fellow of the National Academy of Sciences, Allahabad; and a Fellow of The World Academy of Sciences (TWAS), Trieste. Subsequently, he was elected as an Honorary Fellow by the Royal Academy of Engineering and is a Foreign Associate of the United States National Academy of Engineering. He has been conferred with distinguished civilian honours, including the Padma Bhushan (1987) and the Padma Vibhushan (2001) by the President of India.

The Promise of Biomanufacturing: India's Pathway to Global Leadership in the Next Technological Revolutions

Rajesh S. Gokhale

Scope

As the Indian National Science Academy (INSA) celebrates ninety years of advancing scientific excellence and national progress, it is timely to reflect on how successive technological revolutions have shaped India's development. From the green revolution to the white revolution to the COVID-19 pandemic innovations, each moment underscored that science, when aligned with social need, transforms societies. Today, the world stands at the dawn of another epochal shift — the **Biomanufacturing Revolution** — where biology itself becomes the infrastructure for sustainable production, innovation, and growth. Guided by the **BioE3 Policy (Biotechnology for Economy, Environment, and Employment)** of the **Department of Biotechnology (DBT)**, India envisions a future where biology serves as the foundation of a circular, innovation-driven economy. This article outlines the **strategic roadmap for India's biomanufacturing** breakthrough that can position India to lead the global bio-revolution with responsibility and foresight.

From mechanised to biologized: The next great Technological Revolution

Every few generations, humanity experiences a technological turning point so profound that it redefines how we live, the way we work, and the manner in which we prosper. The first industrial revolution mechanised human effort; the age of electricity and steel illuminated cities and powered industries; and the digital revolution interconnected minds, machines, and markets across the globe. Each revolution lifted productivity and extended life but also introduced new vulnerabilities arising from

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overconsumption to ecological imbalances. Today, the world stands at the brink of the next great transition: the biomanufacturing revolution, where biology becomes the new infrastructure of progress.

Just as the steam engine powered industries and computers powered networks, biological systems such as cells, enzymes, and microbes are now powering a sustainable, regenerative economy. This revolution seeks not just to mechanise, electrify, or digitalise but to biologize the future by embedding life's own logic into the design of technology, economy, and the society. This transformation promises to heal as it builds, to renew as it grows. And India, with the BioE3 Policy (https://bmi.dbtindia.gov.in/pdf/folder.pdf) as a key driver of economy, employment, and environmental goals along with its deep scientific capacity, is poised to take leadership into the new era of bio-revolution.

From famine to food and nutrition security: The early Biological Revolutions

The Bengal Famine of 1943 remains one of the most searing reminders of how technological inadequacy can turn into national tragedy. The devastation shaped India's post-Independence commitment to self-reliance in food. The ensuing green revolution was a triumph of science and policy convergence. Through high-yielding crop varieties, seed and fertilizer innovation, along with irrigation management, India overcame chronic shortages and became self-sufficient in food production. The green revolution was, in essence, India's first biological revolution, a proof that the careful harnessing of living systems could alter social outcomes. It also created the foundations for institutional science, comprising agricultural universities, research councils, and technology missions imparting societal needs.

Yet, as we look back, it reminds us that science must continually balance productivity with sustainability, enhancing yield without eroding nutritional value, and advancing progress without depleting the soil that sustains life. These lessons lie at the heart of the BioE3 approach, which envisions biotechnology-driven solutions that restore soil health, enrich the nutritional quality of food, and regenerate ecosystems rather than exhaust them.

Simultaneously, another transformation — the White Revolution, or Operation Flood followed, which harnessed the power of biological science, systems thinking, and grassroots cooperation to transform India's dairy sector. By integrating animal breeding, vaccination, cold-chain logistics, and farmer cooperatives, India turned from a milk-importing nation into the world's largest milk producer.

However, the next frontier for India's dairy sector brings new and complex challenges. As the demand for milk continues to rise, increasing productivity must be balanced against concerns over greenhouse gas emissions, land and water use, and the feed-food competition that strains agricultural resources. Agrifood system, including agriculture, forestry, and land use (AFOLU) accounted for **23% of global anthropogenic greenhouse gas (GHG) emissions** in 2017, measured over a 100-year global warming potential. **Livestock supply chains** alone contribute **14.5% of human-induced GHG emissions**, with most AFOLU emissions in the form of **methane**. Key sources include **enteric fermentation and manure management in livestock (32%)** and **flooded paddy rice cultivation (8%)** (*FAO. 2022. Methane Emissions in Livestock and Rice Systems — Sources, quantification, mitigation and metrics*). Expanding fodder cultivation exerts pressure on soil health, biodiversity, and freshwater availability. These realities call for a reimagining of the dairy ecosystem, where one integrates climate-smart livestock management comprising **improved feed quality,** nutrient management, genetically improved breeds etc. Thorough genomic and microbial innovations can be adopted to enhance feed efficiency and reduce emissions through modifications such as **targeting methane production genes** and **modifying rumen microbes**. At the same time, alternative protein sources and non-dairy milk options derived from millets, pulses, oats, soy, and algae are emerging as viable complements. These offer opportunities to diversify nutrition, reduce the environmental footprint, and create new value chains aligned with BioE3's vision of sustainability.

The Covid pandemic as a watershed moment: Biotechnology comes of Age

If the Bengal famine exposed the **absence of technology**, COVID-19 revealed its **transformative power**. The pandemic was a defining moment when **biotechnology moved from the laboratory to the heart of the economy** — no longer confined to research institutions but shaping national resilience, public health, and global cooperation.

Within months, India and the world witnessed the power of **biomanufacturing at an unprecedented scale:** vaccines, diagnostic kits, monoclonal antibodies, enzymes, and other critical biomolecules were designed, tested, and produced with remarkable speed. For the first time, the nation saw the **entire spectrum of the bioeconomy in motion**. These ranged from academic breakthroughs and start-up innovations to industrial-scale production and international partnerships that ensured health-equity, access and affordability.

At the centre of this effort stood **Mission COVID Suraksha**, launched by the Department of Biotechnology (DBT) and implemented through the Biotechnology Industry Research Assistance Council (BIRAC). The mission was India's coordinated national strategy to accelerate indigenous vaccine development and scale-up. It strengthened end-to-end capabilities—**from preclinical research and clinical trials to manufacturing infrastructure and regulatory facilitation**—creating an integrated biomanufacturing network that now is a national asset. The mission also laid the foundation for future **pandemic preparedness**, by advancing platform technologies such as **mRNA, viral vector, and protein subunit systems**, and by expanding **biosafety, testing, and manufacturing facilities adhering to GMP** (**good manufacturing practices**) across India. Institutions such as BRIC-THSTI (Biotechnology Research and Innovation Council — Translational Health Science and Technology Institute) and BRIC-NII (National Institute of Immunology) provided necessary clinical analytics for these developments.

COVID-19 marked the moment when biotechnology was no longer seen as a niche science but as a **foundational technology platform that would be v**ital for health, agriculture, environment security, economic growth, and sustainability. This new confidence in biotechnology is now rooted in **India's scientific strength, public trust, and collaborative spirit and** has shaped the country's approach to building a **resilient bioeconomy.**

Growing beyond grains: Redefining conventional expectations from agriculture

Integrated farming is the need of the hour to promote circular economy and achieve sustainable, climate-smart, and food-secure agricultural systems. Sugarcane offers one of the most illustrative examples of a bio-based circular economy in action. Traditionally grown for sugar, the crop has evolved into a multi-product resource that supports food, fuel, and industrial biomanufacturing, all within the framework of resource efficiency and rural livelihoods.

Advances in biotechnology and process engineering can now enable the valorisation of sugarcane biomass into bioplastics, biochemicals, and high-value nutraceuticals, expanding its economic and environmental potential. Converting agricultural residues into ethanol marks a transformative shift, enabling cleaner fuels, reduced pollution, and higher farmer incomes.

In the modern sugarcane circular economy model, every component of the crop is utilized: Juice and molasses are fermented to produce

ethanol, providing a renewable biofuel that has supported India's E20 blending target. India achieved **20% ethanol blending in petrol by 2025**, five years ahead of **the original 2030 target**, with production rising from **38 crore litres in 2014** to **661.1 crore litres**, saving about **Rs. 1.36 lakh crore** in crude imports. India's ethanol manufacturing capacity stands at around 17,000 million litres, spread across approximately 400 production units nationwide. The success of ethanol blending has encouraged the sugar industry to push for higher blending targets, urging the government to establish a roadmap for increasing ethanol blending with petrol to 27% (E27). Bagasse, the fibrous residue after juice extraction, serves as a bioenergy source for co-generation of electricity and steam, often making sugar mills self-sufficient in energy. Press mud is converted into organic manure or bio-compost, enriching soil health and reducing the need for chemical fertilizers. Spent wash from distilleries can be treated and used for irrigation or biogas production, closing the nutrient and energy loops.

Biomanufacturing: Reimagining the future

Biomanufacturing will empower humanity to reimagine production, consumption, and sustainability itself. At its heart lies a simple but revolutionary premise: '***Anything that can be coded by DNA can in-principle be biomanufactured.'*** By harnessing the language of life, biomanufacturing opens the possibility of designing new materials, medicines, and ecosystems that regenerate rather than deplete. However, the far-reaching implications of biomanufacturing require governance and research guidelines that ensure its **ethical and responsible use**. The BioE3 Policy 2024 establishes a comprehensive, discovery-to-application research framework and delineates strategies to bridge the scale-up gap by advancing technologies with validated proof-of-concepts to pre-commercial maturity. The policy seeks to resolve longstanding challenges in India's biotechnology ecosystem by instituting a mission-oriented, collaborative, and innovation-driven approach that fosters robust public–private partnerships. Building upon earlier strategic initiatives, it strengthens scale, integration, and translational orientation, thereby ensuring that research outputs are scientifically rigorous, socially beneficial, and economically viable.

The BioE3 Policy unites six thematic areas under one technological canvas to meet future challenges.

Bio-based chemicals and enzymes: The Indian bio-based chemicals market is poised for substantial growth. Valued at approximately USD 1.5 billion in 2023, it is projected to expand at a Compound Annual Growth Rate (CAGR) of 10%, potentially reaching USD 4-5 billion by 2028. Advancing India's bio-based chemical sector requires a **shift from**

traditional chemicals to sustainable bio-based methods, focusing on strategically important products. The focus will be to drive industrial biomanufacturing in the country to ensure sustainable bio-based production of specialty chemicals, active pharmaceutical ingredients (APIs), enzymes and biopolymers through synthetic biology and genetic engineering, Key actions include **strain engineering, fermentation optimization, efficient downstream processing, and techno-economic and life cycle assessments**. Transitioning to **biomass and biowaste feedstocks**, along with supportive policies like **carbon taxes, sustainability certification, and eco-labelling,** will enhance commercial viability and drive growth in the bioeconomy.

Functional foods and Smart proteins: India's strong agricultural base provides a solid foundation for the production of plant-derived proteins (e.g., soy, pea, millets, and pulses). This advantage is complemented by an emerging ecosystem focused on biotech-driven fermentation-based protein production. The focus will remain to promote sustainable biomanufacturing of smart proteins and functional foods with low carbon footprint using synthetic biology and metabolic engineering tools, with an ultimate aim to provide adequate and nutritional food to the ever-growing population.

Precision biotherapeutics: Precision biotherapeutics use advanced genomics, engineered biologics, and data-driven design to create therapies tailored to an individual's molecular profile. With synthetic biology, AI-enabled modelling, and targeted delivery systems, the shift treatment from population-based approaches to true precision medicine paradigms. India has developed strong indigenous capabilities, including mRNA platforms, large-scale antibody manufacturing, and Cell and Gene Therapies (CGTs), post-COVID. Emerging biomanufacturing technologies such as continuous processing, real-time monitoring, process analytical technology, next-generation cell lines, and AI/ML-driven digital twins with improved efficiency and scalability. For example, the DBT-supported first-in-human Phase I gene therapy trial for Haemophilia A carried out by the Centre for Stem Cell Research (CSCR), a translational unit of BRIC-InStem and CMC, Vellore has demonstrated clinically significant outcomes, marking an important step towards a strong national CGT ecosystem. India's emerging CAR-T cell therapy programs driven by collaborations between leading research institutes such as Indian Institute of Technology (IIT) Bombay, hospitals such as Tata Memorial Centre (TMC), and biotech start-ups are rapidly advancing toward affordable, domestically developed immunotherapies for cancers. Finally, India's substantial rare-disease burden signals not only the scale of the challenge but also the breadth of opportunity to lead meaningful change.

Climate resilient agriculture: Advancing sustainable, green agribiologicals—ranging from microbials and plant extracts to semiochemicals—offers a promising alternative to the intensive use of synthetic agrochemicals. Emerging innovations in gene-editing combined with India's move towards enabling DNA-free, edited crops to be released as conventional varieties are opening a new frontier for rapid, climate-ready agricultural improvements without the regulatory burden traditionally associated with transgenic technologies. Further, the next-generation bio-based inputs, and precision agriculture tools are shaping the next wave of agri-industrial growth. India's bioagriculture sector already contributes about 8.1% (~$13.5 billion) to the national bioeconomy. With consumers and producers increasingly seeking low-chemical, regenerative practices, demand for bio-based agri-solutions is accelerating, opening pathways for both rural innovation and large-scale adoption.

Carbon capture and its utilization: India is rapidly strengthening its position in the global CCU market, which is growing at a CAGR of 13.8% and is expected to reach USD 7 billion by 2030. Biotechnology is becoming a central lever for deep decarbonization enabling bioenergy with carbon capture and storage (BECCS) platforms and biological systems that transform captured CO_2 into fuels, polymers, specialty chemicals, and other high-value products. A national pipeline of innovations is emerging across academic centres, start-ups, and industry R&D teams, focusing on engineered microbes, robust algal platforms, and biocatalytic routes capable of operating directly on industrial flue gases. These efforts are aimed at supporting large emitters, particularly steel, cement, and power, by pairing carbon capture with productive utilization pathways. Together, they signal India's shift towards scalable, biology-enabled carbon mitigation.

Futuristic marine and space research: The global marine biotechnology market is expected to grow at a CAGR of 6.9% between 2025 and 2032, and India's share is projected to expand even faster at 12.6% over the same period, reflecting rising investment in marine resources for sustainable materials, novel therapeutics, blue bioeconomy applications, and climate-resilient innovations. With one of the world's longest coastlines and rich biodiversity stretching from the Arabian Sea to the Bay of Bengal, India is uniquely positioned to build a competitive pipeline of marine-derived enzymes, nutraceuticals, and drug leads. Advances in genomics, bioprospecting, and aquaculture technology offer India an opening to create high-value products while supporting coastal livelihoods. Strategic investment now can place the country at the forefront of the fast-growing global blue biotechnology landscape.

Space is opening an entirely new laboratory for biology, where microgravity, radiation, and isolation reshape cellular behaviour in ways impossible to observe on Earth. Future opportunities range from space-grown biomaterials and novel drug discovery platforms to engineered life-support systems for long missions and planetary habitats. With the rise of commercial stations and biotech payloads, space biology is poised to accelerate innovation in human health, regenerative medicine, and closed-loop biomanufacturing for both terrestrial and off-planet applications. The Axiom-4 mission carried a cutting-edge suite of biotechnology experiments aboard the International Space Station (ISS) that were performed by Group Captain Shukla. Projects ranged from the growth of edible microalgae and cyanobacteria as potential space-food and life-support systems to cultivating traditional crop seeds and sprouts in orbit, testing their germination, growth, and nutritional viability under space conditions. Further, the Axiom-4 mission's muscle-cell regeneration experiment examined how microgravity alters muscle growth and repair, generating insights that could strengthen astronaut health and advance treatments for muscle-wasting disorders on Earth.

The DBT has set up a national biofoundry network—a connected set of high-precision bioengineering facilities meant to give India's biotechnology startups something they often lack: the ability to scale ideas into deployable prototypes quickly and affordably. By offering shared access to advanced design–build–test–learn platforms, these biofoundries facilitate young companies move beyond benchtop tinkering into repeatable strain engineering, high-throughput screening, and early pilot-scale development without heavy capital investment.

A key implementation strategy of the BioE3 policy is strong Centre–State partnership, which ensures that national biotechnology goals are effectively deployed at the regional level by establishing **BioE3 Cells**. The Centre provides overarching policy direction, funding, regulatory frameworks, and national-level infrastructure, while States contribute land, local incentives, skilled workforce support, and region-specific biomass and industrial linkages. This shared responsibility enables efficient establishment of biofoundry network, biomanufacturing hubs, and Bio-AI centres across diverse geographies, promotes balanced regional development, and accelerates commercialization of bio-based innovations. Such coordinated Centre–State collaboration is essential for scaling India's bioeconomy, strengthening biomanufacturing capacity, and ensuring that BioE3 benefits reach both metropolitan and Tier-II/III regions.

Strengthening academic training that is genuinely valued by industry and national missions requires deep, sustained collaborations between academia and the private sector. DBT's new i3C BRIC–RCB

PhD Programme in Biosciences advances this shift by modernizing doctoral training with immersive learning, entrepreneurship exposure, and a problem-solving mindset to drive innovation-led R&D growth. The programme further builds cross-sector agility, preparing scholars to work seamlessly in cross-disciplinary teams engaged in different institutions. By embedding real-world challenges into doctoral projects, it creates a future-ready talent pipeline capable of powering India's expanding biotechnology enterprise.

Building Viksit Bharat with the BioE3 Policy: From bench to bioreactor to business

India's renewed focus on biotechnology is not only evident in policy frameworks and government investments but also in the growing synergy between academia, industry, and start-ups working at the frontiers of science. By integrating research, innovation, infrastructure, and entrepreneurship, DBT aims to transform India into a global bioeconomy leader while addressing pressing environmental and employment challenges. The integration of biotechnology across sectors is creating new opportunities for entrepreneurship, employment, and global leadership in the life sciences. According to recent estimates by BIRAC, India's bioeconomy reached a value of over $165.8 billion in 2023 and is set to cross $300 billion by 2030. Women in science, young entrepreneurs, and grassroot innovators are increasingly finding the support, visibility, and platforms needed to shape the next chapter of India's biotech growth.

Over the past 37 years, the Department of Biotechnology (DBT) has built a strong and steadily maturing innovation ecosystem in India, linking research institutions, industry, start-ups, and bio-clusters into a coherent national network. These efforts continue to push the country towards a future shaped by the unfolding bio-revolution, where biology becomes a central engine of economic and societal progress. In the years ahead, new paradigms of co-evolution—captured in the idea of the Triad of Intelligence: 'Natural, Biological, and Artificial'—will increasingly guide how discoveries are made, technologies are translated, and systems are engineered. Together, these forces are expected to accelerate innovation at a pace and scale not previously possible, driving the next generation of advances in biomanufacturing, healthcare, agriculture, and environmental resilience.

RAJESH S. GOKHALE is Secretary, Government of India at Department of Biotechnology (DBT), Ministry of Science & Technology, on deputation from the Indian Institute of Science Education & Research (IISER) Pune. He has previously held key academic and leadership positions at the National Institute of Immunology (NII) and as Director of the CSIR-Institute of Genomics and Integrative Biology (CSIR-IGIB), where he helped establish its South Campus and launched major programs in disease research and genomics. Trained at the Indian Institute of Science (IISc) Bengaluru and Stanford University, USA, Rajesh Gokhale's research investigates the interactions between metabolism and immunity in diseases such as tuberculosis and vitiligo, leading to the identification of novel therapeutic pathways, as documented in prestigious scientific journals. As a dedicated mentor, he has supervised more than 200 researchers, including 25 PhD candidates, many of whom have achieved significant positions in the global arena. In addition, he is a co-founder of Vyome Biosciences, where he has propelled innovative acne therapies to late-stage clinical trials. His distinguished accolades include the Infosys Prize, the Shanti Swarup Bhatnagar Prize, and the J.C. Bose Fellowship. At the DBT, Dr. Gokhale is driving India's biotechnology agenda towards innovation and sustainability, with the **BioE3 policy vision**—Biotechnology for Economy, Environment, and Employment—as its guiding framework and a focus on affordable biomanufacturing, advancements in genomics, and fostering robust partnerships across various sectors.

Chemistry as the Backbone of India's Scientific Renaissance

Srivari Chandrasekhar

Scope

Chemistry has been the unsung architect of India's scientific renaissance, transforming indigenous knowledge into global innovation. From natural products to generics, agrochemicals to petrochemicals, it has empowered public welfare and industrial self-reliance. The future of the planet's sustainability of materials will depend on how chemistry adapts the circularity of resources more efficiently.

Chemistry has long been the silent architect of India's transformation, and as the Indian National Science Academy (INSA) celebrates its ninetieth anniversary in 2025, its story mirrors the nation's own ascent from colonial-era laboratories to global innovation hubs. What began in 1935 as the National Institute of Sciences has grown into a crucible of ideas, convening luminaries, advising policymakers, and weaving scientific excellence into every strand of India's development. This milestone invites us to reflect on how chemistry — once confined to lecture halls — has become the backbone of agriculture, healthcare, bulk chemical industry and beyond.

In the decades before independence, India's chemical activity was largely academic. Scholars at institutions such as Presidency College and Indian Association for the Cultivation of Science laid important theoretical foundations, but industrial applications remained aspirational. Indian chemistry in the post-independence era began with a deep sense of purpose: to harness indigenous knowledge, build self-reliance, and contribute to national development. The early decades saw a strong

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emphasis on natural products chemistry, driven by Prof. Asima Chatterjee, Dr K. Venkataraman, Dr T.R. Govindachari, Dr S. Swaminathan and others. These researchers were engaged in isolating alkaloids, flavonoids, and terpenoids from India's rich flora and characterising them. This was not just scientific curiosity — it was a strategic response to limited access to imported reagents and a desire to build a pharmaceutical base rooted in local biodiversity. After 1947, establishment of CSIR (Council of Scientific and Industrial Research) laboratories and Indian Institutes of Technology (IIT) catalysed a renaissance towards industrial applications of the research being carried out. Sir P.C. Ray, considered Father of Indian Chemistry, was the founder of Bengal Chemicals and Pharmaceuticals, the first pharmaceutical industry in India. Pioneers, like Dr T.R. Seshadri, Prof. Sukhdev, Dr A.V. Ramarao, Prof. G. Mehta and many others, not only expanded the frontiers of chemistry but set the stage for India's emergence on the global scientific map. Standing in a league of his own, Prof. C.N.R. Rao redefined the very architecture of material science on a global platform which aptly won him the highest civilian honour of India—the Bharat Ratna.

Pharmaceuticals and agrochemicals: Twin pillars of public welfare

By the late twentieth century, chemistry in India had matured into a profoundly interdisciplinary enterprise. Fields such as catalysis, green chemistry, computational modelling, medicinal chemistry, process engineering, chemical biology, and biophysics converged to generate knowledge-intensive innovations—capable of delivering both everyday essentials and frontier therapeutics. Today, one of every five tablets consumed globally originates from India, a testament to the generics industry's brilliance in combining cost-effective process optimization with uncompromising quality standards.

This achievement owes its global stature mostly to the pharmaceutical sector and to the pioneering efforts of CSIR laboratories, notably under the leadership of Dr A.V. Ramarao – a Fellow of this Academy since 1986, the year when I joined his group for my doctoral studies. His contributions, first at the National Chemical Laboratory (NCL) and later at the Indian Institute of Chemical Technology (IICT), laid the groundwork for scalable, affordable drug synthesis. Special tributes are also due to M/s Cipla and Dr. Reddy's Laboratories, guided respectively by Dr Y.K. Hamied and Dr K. Anji Reddy, whose vision and stewardship transformed access to essential medicines to common citizens.

A pioneering effort in antiviral drug synthesis, a practical and scalable route to AZT (Zidovudine), demonstrated India's capability in complex molecule production — laying the groundwork for affordable HIV

treatment. Similarly, an eco-friendly synthesis of IMDG, an Adjuvant used in COVAXIN® for increasing efficacy of the vaccine, during the COVID-19 pandemic, enabled rapid deployment of India's indigenous vaccine. These examples showcase chemistry's role in public health emergencies, both developed by CSIR-IICT stand tall as academic contributions to pharmaceutical industry amongst many technologies developed by Indian national institutes. India's mastery in reverse engineering and process chemistry led to the global dominance of its generics industry – producing 20% of the world's tablets and meeting 60% of global vaccine demand.

The Public-sector undertaking, under IDPL (Indian Drugs and Pharmaceuticals Ltd.) brand, formulated low-cost versions of essential medicines like paracetamol and sulphonamides, ensuring access of essential drugs across rural India for providing better healthcare.

Parallel to the pharmaceutical revolution, India's agrochemical sector has played a transformative role in securing food sovereignty while empowering agriculture-based livelihoods, mostly in rural areas. From the early days of pesticide formulation and fertilizer optimization, institutions like the Indian Agricultural Research Institute (IARI), NCL, and IICT have been instrumental in developing cost-effective, climate-resilient agrochemical solutions tailored to Indian soils and crops. Visionaries such as Dr B.D. Tilak, Dr S. Swaminathan, Dr K. Nagarjan, Dr J.S. Yadav and other synthetic chemists laid the scientific foundation for agrochemicals, fertilizers, and eco-sensitive pest management strategies. Affordable agrochemicals and fertilisers from Public-sector undertakings like IFFCO (Indian Farmers Fertilizer Cooperative), NFL (National Fertilisers Limited) and FCI (Food Corporation of India, Govt. of India) and private players like UPL Limited, Rallis India and PI industries further catalysed this movement, blending innovation with farmer-centric outreach. These efforts, stood by farmers to make India a country leading in food exports with surplus production from the days of PL-480 imports of wheat and frequent famines faced by the country. Incidentally, the old Technology Bhavan (the old building in which DST was initially hosted, where I took charge as Secretary, DST) was the designated godown to store the grains imported to India from USA. The interventions, not only enhanced crop yields and reduced input costs but have also shaped national policy on sustainable agriculture. Much like the pharmaceutical sector, India's agrochemical enterprise reflects a deep-rooted commitment to public welfare – ensuring that scientific progress translates into tangible benefits for millions of farmers across the country. The trajectory of Chemical Sciences in India has been consistently guided by the imperatives of public wellbeing: democratizing healthcare through innovative, low-

cost solutions, and empowering farmers through reliable agrochemical access. These twin pillars continue to resonate across both domestic and international scientific discourse.

Petrochemicals and industrial self-reliance

One sector that has remained relatively overlooked by academic chemists is the crude oil refinery industry. Notably, its downstream segment – spanning the production of bulk and fine chemicals – has been instrumental in bolstering India's industrial self-sufficiency and economic resilience. Yet, its scientific and strategic contributions are seldom acknowledged in mainstream discourse.

Refineries are no longer just fuel processors — they are chemical powerhouses, producing key feedstocks like ethylene, propylene, benzene, and toluene that underpin everything from plastics and textiles to agrochemicals and pharmaceuticals. The emergence of large, integrated petrochemical complexes has enabled value addition across downstream industries such as packaging, automotive, construction, and healthcare. Public and private refiners have expanded capacity to meet rising domestic demand, reducing dependence on imports and positioning India as a regional hub for petrochemical production. The processes followed by this sector stand on par with global benchmark.

Strategic initiatives like the National Petrochemical Policy, Hydrocarbon Vision 2030, and Production Linked Incentive schemes have further accelerated innovation and investment in this space. Notable contributions include Indian Oil Corporation's naphtha cracker complex in Panipat, Reliance Industries' integrated refinery-petrochemical model in Jamnagar, and HPCL's Visakh Refinery modernization — all of which have strengthened India's self-reliance in key chemical intermediates. As India transitions towards sustainable manufacturing and net-zero goals, the refinery sector's pivot to green chemistry, circular production, and bio-based alternatives will be critical in shaping the next chapter of industrial transformation.

Indian universities and research institutes churn out a large number of STEM graduates; however, the gap between academic training and industry-needs remains an area to focus on for better employability of the graduates. Bridging these divides calls for structured academia-industry partnerships, shared laboratories, and fellowship programs that immerse students in real-world challenges and motivates them to provide game-changing, out-of-the-box solutions.

On the innovation frontier, India's patent landscape tells a tale of both progress and friction. The shift to TRIPS-compliant product

patents fuelled the generics revolution, but stringent interpretations of incremental-innovation clauses have sometimes stifled nuanced lead optimization. Meanwhile, most public labs lack dedicated technology-transfer offices and incubation platforms, leaving promising discoveries stranded between bench and marketplace. Cultivating IP literacy, embedding entrepreneurship into curricula, and building translational centres are essential to nurture home-grown technologies.

CSIR-IICT offers a vivid illustration of mission-driven chemistry in action. Its early success in synthesizing the antiviral AZT showcased India's ability to tackle complex drug production. More recently, CSIR-IICT developed an eco-friendly, scalable route to the synthesis of IMDG, an adjuvant used in COVAXIN® — streamlining vaccine deployment during a global emergency and demonstrating how agile, goal-oriented research can serve the public good.

Bridging gaps: Innovation, equity, and the road ahead

Despite a decade of growth in R&D expenditure, India's investment remains at just 0.65 percent of GDP—well below the government's 2 percent target and OECD averages of 2–3 percent. Public agencies and academia account for two-thirds of funding, while private industry contributes under 40 percent — unlike in advanced economies, where it drives three-quarters of R&D spend. The newly carved out ANRF (erstwhile SERB) will certainly bridge this budget gap by attracting private funding into R&D. Talent in smaller cities and private colleges often goes untapped for lack of grants and shared-facility access; democratizing funding through capability-based grants and rigorous accountability can unleash this reservoir of creativity. Some initiatives of public funding agencies (Department of Science and Technology (DST)/Department of Biotechnology (DBT)/Indian Council of Medical Research (ICMR)/ Indian Council of Agricultural Research (ICAR) etc.) with focussed funding to state universities (which cannot compete on merit with already well funded IITs and National Institutes) such as SERB-SURE (State University Research Excellence) including private universities (excellent capital infrastructure is built in these universities but because of lack of research grants from government agencies, the facilities are underutilised), post-graduate colleges and innovative start-ups is essential to bring these institutes at par with other privileged institutes which is very essential to compete on a global scale. Also, a close statistical analysis of funding from government agencies revealed, major funds go to only few states in the union of India. It is very essential to rope in all states to enable equity of scientific knowledge.

Looking ahead, India must balance blue-sky exploration with problem-solving pragmatism. Curiosity-driven research plants the seeds of tomorrow's breakthroughs, while targeted projects address immediate needs in agriculture, healthcare, renewable energy, and smart infrastructure. A thoughtfully diversified portfolio will maximize innovation dividends and ensure no promising avenue is left unexplored.

Recent mission-mode initiatives — such as the National Quantum Mission and the National Supercomputing Mission — signal strategic focus on frontier platforms that will underpin multidisciplinary advances. Coupled with a INR 1 lakh-crore soft-loan facility for industry, these programs offer powerful tools to accelerate high-impact sectors like precision agriculture, advanced materials, and smart housing. Learning from past successes and refining governance will be the key to translating ambition into tangible outcomes.

As INSA embarks on its next decade, its role as mentor, catalyst, and conscience of India's scientific enterprise has never been more vital. By democratizing infrastructure, incentivizing both creativity and real-world impact, and forging global partnerships, the Academy can guide India from fast follower to trailblazer in both fundamental and applied research. In honouring its ninety-year legacy, INSA can illuminate the path towards a future where chemistry continues to enrich lives, empower communities, and shape a sustainable, equitable world.

SRIVARI CHANDRASEKHAR obtained his Bachelor, Masters, and PhD degrees from Osmania University, with his PhD work carried out at IICT on the total synthesis of Cyclosporin. He was an Alexander von Humboldt Fellow at Göttingen University and a postdoctoral fellow at the University of Texas. He has made significant contributions in diverse areas of organic chemistry, especially in chiral chemistry "asymmetric synthesis" and the total synthesis of biologically active natural products. He served as Secretary to Government of India, Department of Science and Technology and Director of CSIR-Indian Institute of Chemical Technology.

Indian Agriculture: Achievements, Current Trends and Challenges

Himanshu Pathak

Scope

Indian agriculture, which has a history spanning over 11,000 years, is the backbone of India's economy, culture, and food security. From the plant and animal domestication of ancient times to the highly diversified and technologically advanced sector of the present day, agriculture has shaped the identity of India and sustained its people. Post-independence science, infrastructure, and policy investments deliberately transformed the country from a food-importing deficit nation to a food-exporting surplus nation. This revolution was marked by historic trends such as the Green, White, Blue, and Horticultural revolutions, accompanied by natural resource management and climate-resilient agricultural system improvements. But Indian agriculture now faces daunting challenges: climate change, degrading water and soil quality, yield stagnation in some crops, and evolving consumer preferences. This chapter looks back on India's farm journey, its environmental diversity, institutional frameworks, milestone achievements, and the role of research and innovation as drivers of growth. It talks of lessons learned and outlines guiding principles for sustainable intensification, precision farming, and inclusive value chains that are national goal-oriented and internationally compliant. The narrative emphasizes that agriculture is not just an economic activity but a cultural tradition and strategic asset for future decades' food, nutrition, economic and environment security.

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Introduction

Indian agriculture is not just a mode of food production, but the pillar of survival, a guardian of heritage, and a bulwark of economic security. With a population of over 1.46 billion, India has to feed the world's largest population while maintaining ecosystems as well as rural economies. The nation covers 328 million hectares (Mha) of land, with an estimated 140 million hectares of cropland, second to the United States only, and has all 15 global climate types and 46 out of 60 known soil types of the world [1, 2].

Historically, Indian agriculture has vacillated between phases of abundance and crisis. Prior to independence, excessive reliance on the monsoon, combined with colonial policy shortfalls, exposed the sector to repeated famines. Between the 18th and early 20th centuries, more than 30 million people died in successive famines [3], the 1943 Bengal famine alone killing 2–3 million. Since independence, though, Indian agriculture has seen a dramatic change. The production of foodgrains increased from 50.8 million tons (Mt) to 354.0 Mt between 1950–51 and 2024–25, pulses from 8.4 Mt to 25.2 Mt, and oilseeds from 5.2 Mt to 42.6 Mt. Cotton increased from 0.5 Mt to 6.7 Mt, sugarcane from 57.1 Mt to 450.2 Mt, and horticulture production from 25.0 Mt to a whopping 367.7 Mt. The agricultural sector also experienced exponential expansion. Milk production increased from 17.0 Mt to 216.5 Mt, fish production from 0.7 Mt to 22.0 Mt, and egg production from 0.9 billion to 138.4 billion units, while meat production increased from 0.5 Mt to 10.1 Mt (Table 1). Now India is a major agricultural exporter, having exported commodities worth Rs. 4.5 lakh crores in 2024-25 [4].

Table 1: *Growth in Agricultural and Allied Sector Production in India (1950–51 to 2024–25)*

Item	Production (Mt)		Increase
	1950-51	2024-25	(X)
Foodgrain	50.8	354.0	7
Pulses	8.4	25.2	3
Oilseeds	5.2	42.6	8
Cotton	0.5	6.7	13
Sugarcane	57.1	450.2	8
Horticulture	25.0	367.7	15
Milk	17.0	216.5	13
Fish	0.7	22.0	31
Egg (Billion)	0.9	138.4	154
Meat	0.5	10.1	20

After 1947, agriculture was given a major support for national food sufficiency and survival. The first Prime Minister of independent India, Pt. Jawaharlal Nehru observed that 'Everything can wait but not agriculture'. Campaigns like the "Grow More Food" campaign [5], supplemented by investment in irrigation, seed systems, and research, laid the foundation for change. Through science-led development, India went from being a "ship-to-mouth" food importer to being a self-reliant and internationally competitive agricultural superpower during the 21st century [4].

Diversity and uniqueness of Indian agriculture

India's agricultural power is in its ecological, genetic, and cultural diversity. India is part of eight global centres of crop plant origin and has more than 166 domesticated species and 320 wild relatives [1]. In these, diversity is huge: rice has over 50,000 known varieties; mango has over 1,000 from the small Nisar to the huge Fazli [1]. This biodiversity supports resilience and has an incredibly large genetic resource base to work with for breeding for climate adaptation and nutritional improvement [4].

Agro-ecological diversity

Four of the globe's 34 hotspots of biodiversity are in India, and the country is home to 8% of the world's known species, even though it accounts for only 2.4% of the total land area of the Earth. Climatic conditions vary from humid tropics of the south to temperate alpine of the north, which dictate cropping patterns and productivity [2].

Water and soils

Water supply is strongly heterogeneous. The Indo-Gangetic Plain enjoys perennial Himalayan rivers and productive alluvial soils, whereas peninsular India uses seasonal monsoon rainfall and possesses scant groundwater recharge. Black cotton soils cover most of the Deccan plateau; lateritic soils cover sections in the east and south [2]. Organic carbon levels are typically below 0.5%, which causes concern regarding long-term fertility [6].

Cropping patterns

States such as Uttar Pradesh and West Bengal produce over 60 crops every year, including cereals, pulses, oilseeds, vegetables, fruits, and spices [2]. The major staples like rice and wheat cover vast areas, while pulses (chickpea, pigeon pea), oilseeds (soybean, mustard, groundnut), and plantation crops (sugarcane, cotton, jute, tea) are both for domestic consumption as well as for export [7].

Livestock and Fisheries

India maintains the world's largest bovine population, with 26 cattle breeds, 17 buffalo breeds, 34 goat breeds, and 44 sheep breeds [2]. Mixed crop–livestock systems dominate, sustaining rural livelihoods and nutrition [7]. Mariculture and capture fisheries provide domestic markets as well as make a substantial contribution to exports, with carp, mackerel, sardine, and shrimp being important species [2]. Such heterogeneity is a strength and a weakness. It provides market diversity and resilience but requires location-specific policies, value chains, and technologies to guarantee balanced growth [5].

Evolution of agricultural research and institutional framework

Studies in Indian agriculture have their roots far back, from Vedic mentions of seasonal patterns to Harappan cultivation of wheat, barley, and pulses [1]. A systematic, contemporary approach started with the formation of the Imperial Council of Agricultural Research in 1929, subsequently the Indian Council of Agricultural Research [2].

Indian Council of Agricultural Research (ICAR) is now one of the world's largest agricultural research networks, with 113 research institutes, 71 agricultural universities, 4 deemed universities, 3 central universities, and 731 Krishi Vigyan Kendras. ICAR's mandate includes crop science, horticulture, livestock, fisheries, natural resources, agricultural engineering, and education and extension [2]. It has propelled developments from high-yielding varieties and biofortification [8] to genomics tools and climate-resilient agriculture systems [5]. Its partnerships with CGIAR centres, international universities, and regional partners have expanded its impact, leading to breakthroughs like the Green, White, Blue, Yellow and Golden Revolutions [7].

Private sector research, farmer innovations, and non-governmental efforts also have increasing roles, particularly in seed improvement, mechanization, and market connections [2]. Together, these players have a sophisticated but complementary system underpinning Indian agriculture's transformation [5].

Major achievements and milestones

Since independence, Indian agriculture has seen a series of path-breaking achievements in a spectrum covering crops, livestock, fisheries, natural resources, and institutions. A synoptic timeline of these achievements is outlined in Table 2.

Table 2: *Chronology of Major Agricultural Milestones in India (1947–2025)*

Period	Milestones
1947–1950s	Initiation of 'Grow More Food' campaign (1947); Community Development Programme for rural extension (1952); Establishment of first Indo-American team recommending land-grant style universities (1955).
1960s	First State Agricultural University at Pantnagar (1960); Release of maize hybrids Ganga-1 and Ranjit (1961); Green Revolution with semi-dwarf wheat (Kalyan Sona, Sonalika) and miracle rice IR8 (1966); Launch of High Yielding Varieties Programme (1966).
1970s	Operation Flood initiated (1970); Establishment of Department of Agricultural Research and Education (DARE, 1973); First Krishi Vigyan Kendra (1974); Creation of ARS & ASRB (1975); Lab-to-Land Programme launched (1979).
1980s	Establishment of NABARD (1982); Fertilizer Control Order issued (1985); Integrated Pest Management (IPM) adopted as national policy (1985).
1990s	Establishment of National Academy of Agricultural Sciences (NAAS, 1990); Release of first hybrid rice APHR 1 (1994); Launch of Institution–Village Linkage Programme (1995); National Gene Bank established (1996); Kisan Credit Card introduced (1998).
2000s	Protection of Plant Varieties and Farmers' Rights Act (2001); Bt cotton approved for commercial cultivation (2002); National Agricultural Innovation Project (NAIP) launched (2005); Release of Pusa Basmati 1121 (2005).
2010s	National Innovations on Climate Resilient Agriculture (NICRA) initiated (2011); Arka Rakshak, first triple-disease-resistant tomato hybrid released (2013); PM-KISAN income support scheme launched (2018); District contingency plans for 650 districts prepared (2018).
2020s	BHOOMI Geo-portal developed (2020); Pesticide Management Bill introduced (2020); Indigenous vaccine for H9N2 avian virus developed (2021); International Year of Millets (2023), More than 100 climate-resilient and biofortified varieties released (2024); Record foodgrain production (354 million tons), horticulture production (368 million tons) (2025).

Field crops

The Green Revolution of the mid-1960s revolutionized Indian food through semi-dwarf, high-yielding varieties of wheat and rice, irrigation, and fertiliser application [7]. Foodgrain production was 354 Mt by 2024–25 compared to 51 Mt in 1950–51 [2]. Later "revolutions" focused on specific commodities:

Yellow Revolution (oilseeds): Production increased from 5.2 Mt during 1950–51 to 42.6 Mt during 2024–25 after the National Mission on Oilseeds [2].

Pulse Revolution: Production increased from 8.4 Mt during 1950-51 to 25.2 Mt during 2024–25 due to varietal improvement and increased cultivation [2].

Sugar Revolution: Sugarcane production increased from 57 Mt in 1950–51 to more than 450 Mt during 2024–25 [2].

ICAR has developed more than 6,000 crop varieties, among which more than 2700 are climate resilient and 200 are biofortified with

improved iron, zinc, protein, or provitamin A [8]. Breeder seed production systems have consolidated varietal replacement rates, and India is now the global leader in Basmati rice trade [7].

Horticulture

India is the second-largest fruit and vegetable producer in the world, with output in 2024–25 standing at 368 Mt [2]. There have been gains through hybrids in mango, coconut, and vegetables; tissue culture in banana (currently 45% of national area); and export-market improvements in grapes and pomegranate [2]. Sea-route export protocols of mango and banana have lessened costs, and standards of quality have improved competitiveness in international markets [5].

Animal husbandry

Operation Flood (1970) transformed India from a milk-deficit country to the world's largest producer, at 217 Mt in 2024–25, and per capita availability of almost 400 g/day [5]. Genetic enhancement, preservation of native breeds, and disease vaccines for avian flu and brucellosis have improved productivity and health [2]. Poultry production has taken off, and India has emerged as one of the principal producers of eggs and broiler meat [7].

Fisheries

The Blue Revolution propelled India to the status of second-largest fish producer in the world [2]. Developments comprise the "Jayanti Rohu" strain with a growth rate of 17% above normal, composite fish culture, and marine cage farming for high-value species [7]. The productivity of carp ponds increased from 0.6 t/ha/year to 10 t/ha/year [2].

The Water-Energy-Food (WEF) nexus strategy brings together sectoral requirements to sustain ecosystem integrity while promoting development objectives. It helps directly achieve several Sustainable Development Goals and enables climate-resilient agricultural planning [4].

Natural resource management

ICAR has surveyed soils at state and national levels [2], created gypsum-based reclamation of sodic soils [6], and encouraged soil health cards and carry-along kits [2]. Water conservation techniques, drip fertigation, and integrated farming system (IFS) models have enhanced the efficiency of resources [7].

Agricultural engineering

Mechanisation technologies are for *in-situ* management of straw, zero-till drills, and laser-guided levellers [8]. Energy-saving irrigation, solar-powered technology, and post-harvest equipment have minimized drudgery, losses, and expenses while increasing productivity [2].

Supporting pillars of growth

Agricultural education

Agricultural education has grown from a small number of colonial-period colleges to a massive network of 71 State Agricultural Universities (SAUs), 4 Deemed Universities, 3 Central Agricultural Universities, and multiple faculties of general universities [2]. These colleges adopt the ICAR-accredited curriculum that combines theoretical teaching with field work [1]. Incorporation of innovative topics—biotechnology, climatology, GIS-based land use planning—makes graduates industry-ready with a foundation in practical problem-solving [5]. ICAR's National Agricultural Higher Education Project (NAHEP) has enhanced infrastructure, faculty development, and global partnerships, facilitating students to have joint research and internships overseas [2]. Alumni linkages and industry connections have enhanced employability and promoted entrepreneurship in agri-startups, food processing, and allied industries [7].

Agricultural extension

The Krishi Vigyan Kendras, with more than 731 centres, are the backbone of India's agricultural extension network [2]. They connect research and practice by conducting on-farm trials, demonstrations, capacity-building programmes, and advisory services [5]. ICT-based platforms such as the Kisan Call Centres (KCCs), mKisan SMS Portal, and mobile applications offer advisories to farmers in local languages at the right time [2]. The Farmer FIRST programme redefines extension by siting farmers as innovation partners and not passive recipients, making technology adoption need-driven and participatory [7].

Collaborations

Collaborations among public research organisations, private enterprises, NGOs, and global agencies have been instrumental to agricultural advancement [2]. ICAR's partnerships with CGIAR centres have provided better varieties of wheat, rice, pulses, and millets [5]. Collaborative ventures with private firms have increased hybrid seed coverage, mechanisation products, and digital agriculture platforms [8].

Policy innovations

Policy frameworks have determined incentives and resources [7]. The National Food Security Act (2013) ensures subsidised grain for 67% of the population [2]. Pradhan Mantri Krishi Sinchayee Yojana encourages "more crop per drop" irrigation efficiency [6]. Minimum Support Prices (MSP) stabilize incomes, whereas e-NAM (National Agriculture Market) provides a unified online market for agricultural produce [7].

Reflections and lessons learned

Success factors

Science-led growth: The combination of crop/breed improvement, natural resources management, crop/breed protection and mechanization has been the key to productivity increases.

Institutional resilience: ICAR and state systems have weathered external and internal shocks to Indian agriculture while reaching out to more people.

Farmer adaptability: Quick adoption of high-yielding varieties/breeds, crop protection and soil and water management technologies reflected farmers' willingness to adapt when risks are neutralized.

Gaps and missed opportunities

Trade-offs for sustainability: Yield-increasing high-input systems depleted aquifers and eroded soils in some areas.

Diverse benefits: Rainfed zones, where the majority of smallholders were located, fell behind irrigated zones in productivity increases.

Volatility of markets: Poor post-harvest infrastructure has exposed farmers to price collapses.

Guiding insights

Interventions in the future need to be location-specific, blending traditional wisdom with scientific knowledge, and prioritizing diversification to act as a buffer against climate and market shocks.

Emerging challenges

India's agricultural economy is confronted with a myriad of upcoming challenges precipitated by climate change, resource limitations, demographic changes, and socio-economic transformations. Estimates suggest that a 1°C increase in mean temperature may decrease wheat production to the extent of 6 million tonnes, seriously jeopardizing national food security. By 2047, per capita access to agricultural land

is likely to decrease to merely 0.09 ha, well short of the world average of 0.5 ha, thereby intensifying scarcity. In the same manner, per capita water availability is likely to decrease to 1,200 m^3, further straining farming systems.

Population dynamics add to these problems. India's population is likely to go up to 163 crore in 2047, whereas the contribution of agriculture to GDP is likely to decline from 18% to 6%. Farm workers are likely to decline from 45% to 25% due to urbanisation (rising from 35% to 55%) and rural youth moving out to non-agricultural sectors. However, with the forecasted hike in per capita income to Rs. 15.4 lakh, consumption patterns and market demands are likely to change [4].

Climate change

Irregular precipitation, heatwaves, and extreme climate events pose risks to India's main crops' yields. Wheat yield, for example would decrease by 6–23% if no adaptation occurs [9]. Climate-resilient agricultural practices and crop varieties, rescheduled sowing dates, and water-saving irrigation systems are essential to reduce risks.

Resource degradation

Groundwater overexploitation has hit record heights in areas like Punjab, Haryana, and Gujarat, whereas soil organic carbon has fallen below sustainable levels in the majority of districts. Excessive use of fertilisers has led to nutrient imbalance and eutrophication, necessitating better management of soil health and balanced nutrient application.

Market and demand changes

Increased urbanisation and rising incomes are changing consumer tastes away from staple cereals to fruits, vegetables, dairy, poultry, and processed foods. Meeting this changing demand will need investment in cold chains, processing facilities, food safety infrastructure, and logistics systems.

Socio-economic stress

The farm size has reduced to 1.08 ha on an average, constraining mechanisation, productivity increases, and economies of scale. Moreover, youth migration to non-farm sectors is eroding generational connections to agriculture, threatening future agricultural sustainability. Priority areas of focus in the Amrit Kaal are the characterization of genetic resources, aligning the water-energy-food nexus, the development of the circular bioeconomy to reduce waste, and working towards a zero-carbon pledge

for agriculture. These need integration of biotechnology, precision farming based on artificial intelligence, and climate-resilient agriculture to achieve sustainable productivity and farmer prosperity [4].

Way forward

Indian agriculture is at a turning point where the attention needs to be diverted from resource-demanding growth models towards resilient, sustainable, and technology-led pathways. By 2047, India's agri-food systems will experience transformational shifts in production, consumption, and trade patterns. Whereas foodgrain production is estimated to increase from 354 Mt in 2024–25 to 520 Mt by 2047–48, and horticulture production from 368 Mt to 950 Mt, these increases need to be done without further loss of land, water, and biodiversity resources. To meet this vision, a multi-pronged approach is necessary.

Shift to climate-smart agriculture

Priority areas are:

1. Breeding, planting climate-resilient, stress-tolerant crops;
2. Reforming sowing calendars to synchronize with changing rainfall patterns;
3. Scaling up micro-irrigation (drip and sprinkler systems) to reach 60% water-use efficiency;
4. Encouraging carbon-neutral farming and zero-carbon agriculture commitments;
5. Embedding AI-based early warning systems for drought, floods, and infestation attacks.

Efficiency and resource sustainability

With natural resources facing unprecedented pressure, the efficiency of resource use has to improve:

1. Increase nitrogen-use efficiency from present 35% to 55% through site-based nutrient management and biofertilisers;
2. Bring post-harvest losses down from 20% to 5% by investing in cold chains, warehousing, and processing facilities;
3. Increase integrated farming systems integrating crops, livestock, and fisheries for more returns per unit of land;
4. Embrace circular bioeconomy approaches to convert farm waste into energy, compost, and higher-value products.

Table 3. *Projected Growth of India's Agri-Food System (2024–25 vs. 2047–48)*

Parameter	2024-25	2047-48
1. Foodgrain (Mt)	354	520
2. Horticulture (Mt)	368	950
3. Rice (Mt)	150	223
4. Wheat (Mt)	118	185
5. Nutri-, coarse cereals (Mt)	51	142
6. Milk (Mt)	217	580
7. Fish (Mt)	22	49
8. Meat (Mt)	10	30
9. Egg (Billion)	138	543
10. Farm mechanization (%)	47	70
11. Post-harvest losses (%)	20	5
12. Water use efficiency (%)	40	60
13. Nitrogen use efficiency (%)	35	55
14. Crop insurance coverage (%)	30	90
15. Share in agri-export (%)	2.4	10

Leverage digital and precision technology

India's future in agriculture will be reliant on digitisation and precision agriculture:

1. Leverage AI, IoT, drones, and satellite imaging for real-time crop monitoring and optimizing resources;
2. Establish farmer-centric mobile systems offering actionable advisories on weather, markets, and pest threat;
3. Implement blockchain-enabled traceability solutions for exports further to solidify India's role as a global agri-export hub;
4. Increase e-NAM and digital markets so that farmers can get transparent, competitive prices.

Diversification and value addition

Changing consumer choices, increasing incomes, and urbanization will transform India's food demand by 2047:

1. Production of horticulture is set to almost triple to 950 Mt, needing more robust cold chain and processing systems;
2. Milk production is set to grow from 217 Mt to 580 Mt, and fish production from 22 Mt to 49 Mt, generating new opportunities for agribusiness and exports;

3. Support food processing clusters close to production areas to minimize wastage and enhance value realization for farmers;
4. Reinforce branding, packaging, and certification systems to access world markets, with a vision of a ten-fold expansion of agricultural exports from 2.4% to 10% of total exports by 2047.

Social inclusion and rural prosperity

The population transition will cut the farm workforce from 45% in 2025 to 25% in 2047, necessitating focused interventions:

1. Encourage farm mechanisation to achieve 70% coverage by the year 2047;
2. Empower women, youth, and smallholders through access to credit, skill training, and FPO strengthening;
3. Promote entrepreneurship in high-value agriculture such as floriculture, organic farming, apiculture, and aquaculture;
4. Develop strong rural economies through decentralised food processing clusters and rural innovation hubs.

Policy and institutional reforms

Policy convergence will be key to fulfilling the objectives of Viksit Bharat 2047:

1. Switch from input subsidies to performance-based incentives tied to sustainability performance;
2. Foster integration of renewable energy into irrigation and processing;
3. Improve public-private partnerships in R&D, infrastructure, and market linkages;
4. Increase global trade competitiveness by improving export logistics, quality certification, and bilateral agreements.

Conclusion

Indian agriculture is at a watershed in its long and illustrious history. From the initial domestication of crops to the Green, White, Blue, and Horticultural Revolutions, India has time and again shown an unparalleled ability to learn and evolve its agri-food systems. At present, though, the sector confronts an unprecedented convergence of challenges: climate change, natural resource decline, fragmented farm ownership, consumer trend shifts, and socio-economic transformation. They necessitate a shift

towards input-scarce, resource-efficient systems of production that are sustainable, regenerative, and climate-resilient.

The next few decades, particularly the Amrit Kaal (2023–2047), present a chance to reboot Indian agriculture as a globally competitive, inclusive, and nature-friendly system.

With science-based policy, digital transformation, and inclusive innovation, India can move from being the greatest food producer to being a global leader in sustainable agriculture. By balancing productivity, profitability, and ecological stewardship, India can attain food, nutritional, and environmental security for its people while making a valuable contribution to global sustainability and zero-carbon goals.

The path forward calls for collective action in convergence of research, policy, industry, and farming communities to develop an agricultural ecosystem that is resilient, competitive, and future-proof. Through strategic investments, revolutionary technologies, and farmer-first strategies, India can actually realize the vision of Viksit Bharat 2047 and become a Vishwaguru of sustainable agriculture.

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Dr Pathak has over 33 years of experience in the global agricultural landscape, particularly in the areas of climate resilience, soil and crop management, and sustainable agricultural systems. He holds a PhD in Soil Science and Agricultural Chemistry from the Indian Agricultural Research Institute, New Delhi and held prestigious fellowships and international research positions. He has published over 200 research papers and 20 books with more than 31,500 citations and 300 i10-index.

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Advanced (SPACE) Technology for Man and Society

P.S. Goel

There are some who question the relevance of space activity in a developing nation. To us there is no ambiguity of purpose. We do not have the fantasy of competing with the economically advanced countries in exploration of Moon or the planets, or manned space-flight. But we are convinced that if we have to play a meaningful role nationally or in the comity of nations, we must be second to none in the application of advanced technologies to the problems of Man and Society.

— Prof. Vikram Sarabhai, 1964

Scope

In the year 1963 the Space Program in India was inititiated by Prof. Vikram Sarabhai with a larger vision using advanced technologies for man and society, from an old church building in Thumba, north of Thiruvananthapuram, to conduct ionospheric studies. He immediately started development of launch vehicle SLV-3, and a 40 kg satellite RS-1, to be launched in a 400 km orbit. This was later pursued by his successor Prof. Satish Dhawan. India entered Space Age by launching the first satellite ARYABHATTA on April 19, 1975 on a Russian launch vehicle under the guidance of Prof. U.R. Rao. A series of satellites with increased complexity and sophistication for Remote Sensing and Communication were later developed by ISRO to serve the "Man and Society." Parallelly, ISRO developed PSLV and GSLV launch vehicles with high reliability and success. Making use of these state-of-the-art launch vehicles and satellites, ISRO is now extending the mandate of its Founder by missions to explore the Universe, the Moon, and the Mars. The program now has taken multiple dimensions of space-based services, scientific explorations, commercial space, and space for national security.

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The start of the Space Program of India

Indian Space Program had a humble beginning by setting up a rocket launching station in an old church building in Thumba (Thumba Equatorial Rocket Launching Station, TERLS), near Thiruvananthapuram in 1963 by Prof. Vikram Sarabhai, for collecting scientific data near the magnetic equator. An American rocket Nike Apache was launched with the association of NASA. Indian Space Research Organization (ISRO) was created in 1967 by creating Space Science and Technology Centre (SSTC) at Velly hills near TERLS with a mandate to build a launch vehicle for putting a 40 Kg satellite into a circular orbit. Various disciplines for developing launch vehicle were created as divisions, including a Satellite Systems Division (SSD) for building satellites.

Numerous sounding rocket projects, RH-75, RH 125, RH 350, RH 500 were undertaken to develop various elements of rocketry like solid propulsion, structure, aerodynamics, and instrumentation. The first target of Satellite Launch vehicle (SLV-3) was set by Prof. Sarabhai to launch a 40 Kg satellite RS-1 into a 400 Km circular orbit. SSD was to develop the RS-1 spinning satellite.

Unfortunately, Prof. Sarabhai suddenly passed away on December 30th, 1971, in sleep at the young age of 52 years, in hotel Kovalam, near Thiruvananthapuram. Prof. M.G.K. Menon took over as interim Chairman till Prof. Satish Dhawan returned from his sabbatical at CALTECH. In his short life, Prof. Sarabhai created 29 institutions including the Indian Institute of Management, Ahmedabad, Ahmedabad Textile Industries Research Institute, Physical Research Laboratory and Indian Space Research Organization, to name a few. In February 1972, the President of USSR visited India and offered a proposal to Prime Minister, Mrs. Indira Gandhi to help in the development of an Indian satellite to be launched by a Soviet launch vehicle.

The Prime minister accepted the offer and the project Indo-Soviet Satellite Project (ISSP) was born with Prof. U.R. Rao as project director. Prof. Satish Dhawan returned from his sabbatical at CALTECH and took charge as Chairman ISRO in June 1972. This started a new era of ISRO, creating Department of Space and Space Commission on the lines of Atomic Energy Commission. The project ISSP moved to Bangalore so as to make use of better infrastructure like Hindustan Aeronautics Limited, Bharat Electronics Limited, Hindustan Machine Tools etc. Starting from empty sheds in Peenya Industrial Estate in Bangalore, ISSP saw a fast pace of activity, establishing laboratories, fabrication facilities, satellite integration facilities, clean rooms, test facilities like vibration, hot and cold, thermovac chambers, recruitment of new manpower that increased scientists/engineers from about 20 at SSD to about 50. The

satellite ISSP was launched on April 19th 1975, and named Aryabhatta, after the 5th century mathematician/astronomer who was the first to lay the foundation of current decimal number system. Aryabhatta satellite was an inspiration to the whole country, that it could develop Advanced Technologies on its own.

Satellite program

With minimum modifications to Aryabhatta satellite, Prof. U.R. Rao decided to make a remote sensing satellite, and Satellite for Earth Observation (SEO) was conceived. India was the first country to carry out remote sensing measurement through a spinning satellite. It accommodated a two-channel vidicon camera and a three-channel microwave passive radiometer. Two of these satellites Bhaskara-1 (launched in 1979) and Bhaskara-2 (launched in 1981) were named after other great mathematicians/astronomers Bhaskaracharya-1 and Bhaskaracharya-2, of 7th and 12th century, respectively.

An opportunity came from European Space Agency for a free geostationary transfer orbit (GTO) launch on the third developmental flight of Ariane launch vehicle. ISRO seized this opportunity, took it as a challenge to develop an experimental 3-axis stabilized communication satellite APPLE (Ariane Passenger Pay Load Experiment). Launched in June 1981, APPLE was a major step in satellite technology, and a big success. The two communication transponders provided good experience in satellite communication, prior to INSAT-1A, a satellite procured from USA, launched in April 1982. India had used one advanced communication satellite of NASA, ATS-6 for the project Satellite Instructional Television Experiment (SITE), to beam education cum entertainment program in 1975-77. This covered 2400 villages, numerous rural clusters in six states and was amongst o the largest societal projects in the world. ATS-6 was a result of NASA's commitment to Prof. Sarabhai, and NASA kept its promise to the great scientist.

The LANDSAT series of Remote Sensing satellites of NASA were becoming popular, and ISRO decided to undertake the development of a state-of-the-art satellite Indian Remote Sensing Satellites (IRS). IRS-1A was launched in March, 1988, and its twin IRS-1B was launched in August 1991. The Space Application Centre (SAC) at Ahmedabad developed both the payloads, and its application algorithms, and along with National Remote Sensing Agency (NRSA), implemented these in the field. With time, India became a leader in the application of satellite remote sensing, fulfilling the goal set up by the founder. IRS-1 was followed by a number of remote sensing satellites, namely IRS-1C, 1D, Resourcesat-1 and CARTOSAT satellites that had even higher spatial resolution. The

notable technology milestone missions include CARTOSAT-1 with stereo imaging capability, CARTOSAT-2 series for high resolution (1 meter or better), OCEANSAT with an eight (channel) ocean color monitor.

Starting from INSAT-1, India had adopted a methodology of multi-mission communication satellites including satellite communication, satellite TV broadcast and a Very High-Resolution Radiometer (VHRR) for meteorology, and wanted to retain the same concept for INSAT-2, to be developed in ISRO. The VHRR requires a passive cooler to cool the detector to about 100K, adding to the complexity. The first INSAT-2 was launched by ARIANE launch vehicle in July 1992. Subsequently, it was followed by four of INSAT-2, five of INSAT-3 and INSAT-4 each with increased fine tuning the payload as per country's need in C, S, Ku and Ka bands. Currently, ISRO is launching high throughput satellites with transponders capacity up to 100 GBPS, at par with rest of the world.

The Kargil war was a reminder that ISRO had not done its due, to support armed forces and therefore a new project was undertaken in June 1999 to provide 1-meter resolution and developed 12 new technologies (hence named Technology Experimental Satellite, TES) in just two years.

Another interesting mission was jointly taken by ISRO Satellite Centre (ISAC) and Vikram Sarabhai Space Centre (VSSC) for re-entry and Spacecraft Recovery Experiment (SRE). Rather than just a re-entry module, ISRO developed a satellite that could remain in orbit for months and years, before initiating the reentry operations. This provided valuable experience for the manned mission (Gaganyaan), now being planned for late 2026.

Satellite navigation

The Global Positioning System of USA has revolutionalized the day-to-day life of citizens everywhere in the world. GPS has made the travel very convenient and supports many service enterprises. However, USA GPS is a system owned by the military and non-availability of GPS can have a devastating impact on any country's economy and security. Due to this reason, many similar global positioning systems have been developed such as Galileo of Europe, BeiDou of China, QZSS of Japan and Glonoss of Russia. ISRO developed a novel regional system IRNSS with name NavIC comprising 11 geosynchronous satellites (as against 28 of USA) but capable of providing similar service over the region of interest and without need for establishing supporting ground stations beyond the Indian territory. This implies a saving on substantive maintenance costs. The concept has been fully validated and the constellation is in the making.

Advanced technology for man and society

Almost all satellites that have been launched had immense societal service component. Thus, remote sensing or communication have been put to the service of people through development of applications in SAC/ISRO and disseminated to people through National Remote Sensing Agency, Regional Remote Sensing Centers, and these have been engaging various agencies of governments and NGOs. Major areas of application include agriculture, weather forecast, disaster warning and management, infrastructure planning, and governance.

One area that remained untouched till late 1990s was the national security. Space is dual use technology and that is why it is treated as strategic department. There is now a considerable focus on application of Space for National Security through large program under Space-Based Surveillance (SBS-1 and SBS-2), Space based intelligence systems (Kautilya and others).

Launch vehicle program

The first experimental launch of the launch vehicle SLV-3 was on 10th August, 1979, and after four flights, it was upgraded by attaching two strap-on boosters to the first stage, to increase the payload capacity to 150 kg from 40 kg of SLV-3. This was named as Augmented SLV or ASLV. The first two flights of ASLV were not successful, but the two subsequent flights were successful. However, the ASLV program was closed as it was not able to lift IRS series of satellites. Development of next launch vehicle named as Polar Satellite Launch Vehicle (PSLV) was started in mid 1980s with a first stage solid booster carrying 139 tons of propellent, S1, a second bi-propellant L-40 stage, a third solid stage S7 and a 2-ton liquid fourth stage to fine tune the orbit. PSLV was initially designed to carry IRS-1 class 1000 Kg satellite to 1000 Km polar Sun Synchronous orbit and later upgraded to even heavier satellites up to 1500 Kg. Over the years PSLV has been heralded as of one of the most reliable launch vehicles in the world and its 61st launch was in May 2025.

Program GSLV (geostationary satellite launch vehicle) was undertaken to launch communication satellites into Geostationary Transfer Orbit (GTO). To make quick progress, four liquid L-40 stages of PSLV were strapped-on to S1 of PSLV, and the second stage was the same liquid L-40 stage. Third stage was a cryogenic stage with 12-ton LOX and H2 propellants. The cryo-stage was procured from Russia, calling this as GSLV Mark-1, able to take up to 1800 Kg satellite into a GTO, and the first flight took place in April 2001. Later, the Indian cryo-stage replaced the Russian, calling it Mark-2, that also included other improvements.

As the INSAT satellite services were increasing, so was its weight, hence, a new configuration was developed to make it more efficient and increased ease of operations with GTO capability up to 4000 Kg. An all new, solid 200-ton motor was developed and two of these were strapped on to a newly developed twin engine L-110 stage. First stage consists of L-110 with two S-200 strap-ons. Strap-ons separate after their burnout and L-100 continues till its propellent lasts, calling it as one and a half stage. A new cryo-stage with 25 LOX and LH2 was developed, C-25, making as second stage, calling this vehicle as GSLV MARK-3. With many successful flights, it is now an operational vehicle and the same is being ruggedized for human rating for manned flights of Gaganyaan.

Advanced communication satellites are now designed for multi beam high throughput of up to 100 GBPS, using power in the range 12 to 15 KW, and with a weight exceeding 5000 kg in GTO. To cater to these requirements in future development of semi cryo-boosters' has been initiated. Studies are being conducted on cluster configurations.

Science programs

Globally, scientific explorations in space have been the drivers of many complex technologies like large telescopes in orbit. India has been actively participating in space science missions from Aryabhatta days when it carried three scientific payloads. Science laboratories like the Physical Research Laboratory, Tata Institute of Fundamental Research, National Physical Laboratory and others have been involved in making scientific payloads. IRS-P3, Chandrayaan-1,-2,-3, Megha-Tropiques, Mars Orbiter, Aditya L-1, Mission to Mars and Astrosat have been major space science missions.

With major focus on Manned Mission -- the Gaganyaan, next two years will be largely oriented towards validation of technologies for manned mission. This will include safe return of the astronauts under any emergency conditions. Also, it is planned to launch two data relay geostationary satellites to provide near continuous coverage of the Gaganyaan.

The challenge for next few years lies in maintaining the tempo of programs for public good. This will largely be focused on remote sensing satellites, national security programs and advanced space exploration missions.

Technologies developed

ISRO has been the power house of technology development and has used expertise in the country whereever available. Many of these

technologies are of dual use, finding application for other civil uses, have been transferred to the industry.

Launch vehicle related technologies are in the area of materials, propellants, avionics, inertial sensors, aerodynamics and structures. Cryogenic engines need materials that do not loose properties at cryogenic temperatures, and handling tons of Hydrogen requires safety protocols. Yet another area is simulation of processes like combustion, rocket trajectory and guidance.

Satellite technologies also need many of the areas above, but adaptation to hard vacuum for years. Making use of solar power, and managing eclipse for one third of time in every orbit, avionics, radiation tolerance, and building reliability for instruments to work for long years in harsh environment. One important component of satellite technology is the development of payloads; remote sensing, communication, scientific, each mission with a specific requirement. Many of these technologies have repeated use and such technologies have been transferred to the industries after the development, while one time use type of technology have been retained within ISRO.

Yet another important technology development has been to use the satellite data, or the satellite communication payload utilization, developing the equipment on ground for best use of space infrastructure. One of the high points of Indian Space program is its relevance to the society. India has been a global leader in the application of space capability for societal well being.

Future outlook

Indian space program has taken a major directional change in last few years. So far, all the programs were conducted by ISRO alone. This approach restricted the spread of technologies to the industry, except those heavily involved like the Hindustan Aeronautics Limited and Larsen & Tubro. A new body, Indian National Space Promotion and Authorization (IN-SPACe) has been created to promote industry participation and encourage start-ups in space sector, not only in fabrication, but also in designing and testing. This is a new paradigm and we will need to see how it works after two to three years. Ideally, for the public good, repeat satellites should be manufactured by the industry and ISRO can then focus on challenging missions of space/planetary explorations Moon and Mars, Venus as also Manned missions. Will the industry now enter in to space technology, be able to absorb the technology and deliver at the highest levels of technology in an environment of lowest quotations raises many question marks. Space related activity needs enormous resources,

and all this has to come only through government funding. The so-called space business is really a myth, globally as all the space based services for the public good, except communication services, are being supported by the respective governments. This includes Satellite Navigation.

Emergence of new technologies like Artificial Intelligence, Quantum technologies, synthetic biology will expand the space applications at an exponential rate. Application of 512 channel Hyper Spectral images will truly emerge only when AI&ML and Quantum Computers are accessible to researchers and academia. Future weather and monsoon forecast would likely depend only on satellite-based data.

The strategic applications of space technology will get boost from hyperspectral imaging crossing the RF boundaries on both sides, lower frequencies to VHF and higher frequencies to Ka band. This will ensure that there may be no place for the enemy to hide except deep inside bunkers. This may lead to war in space, destroying adversary's assets in space, what was called Star Wars in the Cold War time of the 1970s.

The possibility of inhabiting Mars and Moon may open up in totally new paradigms in science, answering some of the unanswered questions and perhaps raising many more new ones.

Let us hope that the emerging scientific leadership will keep the words of Prof. Sarabhai as a beacon while pursuing new endeavors in the world of uncertainties resulting from new technology waves, not yet surfaced or hitherto imagined.

P.S. GOEL was Secretary, Department of Ocean Development (DoD) and was responsible for transforming DoD into Ministry of Earth Sciences (MoES). He was the first Chairman of Earth Commission. He oversaw commissioning of Tsunami Warning System of India, initiated the modernization of IMD and pursued exploration of deep oceans. Currently, Dr Goel is Honorary Visiting Professor at National Institute of Advanced Studies. He is chairing Technology Research Board (TRB) of Ministry of Earth science.

Dr Goel contributed significantly to the mission planning for remote sensing, communication and scientific missions and authored over hundred research papers in referred journals and conferences. Dr Goel was Chairman of spacecraft systems for IRS-1, Project engineer AOCS for APPLE and Associate Project Director, INSAT-II. He was Director ISRO Satellite Centre from 1997 to 2005 and a member Space Commission. He was President of Indian National Academy of Engineering (INAE) and Vice President, Aeronautical Society of India, Dr

Vikram Sarabhai Distinguished Professor of ISRO. Dr Goel was awarded the Padma Shree in 2001. He received several other awards including Distinguished Scientist Award of ISRO and life time achievement award of INAE. He is fellow of Indian Academy of Sciences, Bangalore; National Academy of Sciences, Allahabad; Indian National Science Academy (INSA), New Delhi; Institution of Electronic & Telecommunication Engineers, New Delhi; Aeronautical Society of India, Bangalore; and Third World Academy of Sciences. He is also a Member, International Academy of Astronautics, Paris.

A Few Milestones in Indian Earth Sciences Since 1967 – Insights from My Professional Journey

Harsh K. Gupta

Scope

I have had the good fortune to be associated with a few important Earth science related milestones in India. These include: 1. Setting up of a Seismological Observatory conforming to WWSSN specifications at Hyderabad without USGS's help. The only one globally. 2. Discovery of 65-70 km crustal thickness below the Himalaya and Tibet Plateau. 3. Discrimination of artificial water reservoir triggered seismicity from normal earthquakes. 4. Earthquake forecasts in northeast India and Koyna, that came true. 5. Setting up of Dakshin Gangotri in Antarctica. 6. Steering G-SHAP global effort where some 500 scientists worked globally during 1992-1999 to produce Global Seismic Hazard Map. 7. Hosting the First Chapman Conference in Asia on the Stable Continental Region earthquakes. 8. Commissioning low temperature thermal desalination plant in Kavaratti in 2005: first one globally. 9. Setting up of Indian Tsunami Early Warning System. 10. Publishing of the Encyclopedia of Solid Earth Geophysics in 2011 and its second edition in 2021. 11. Developing Earthquake Scenarios, and 12. Efforts to develop an Earthquake Resilient Society in India. 13. Representation of Indian Earth Scientists in the concerned International Organizations and related activities. In this write-up a glimpse of these milestones is provided.

Indian National Science Academy's bringing out of the Legacy Volume covering significant work having been carried out in India in different scientific disciplines is a very welcome initiative. My scientific career started in 1963 when I joined the Central Seismological Observatory, Shillong on the 27 May 1963. I have had the good fortune of working

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with several Institutions in India and abroad. In the following a few of the noteworthy contributions that I have been involved in are briefly mentioned.

Seismological Observatory at CSIR-NGRI, Hyderabad

During 1963-64, the United States Geological Survey (USGS) came up with a scheme of setting up of ~120 seismic stations equipped with 3 matched components each of short period Benioff and long-period Press-Ewing seismographs, globally. The purpose was to obtain standard data about earthquakes. It was called the World-Wide Standard Seismograph Network (WWSSN). The CSIR-National Geophysical Research Institute had a new Director, Dr. Hari Narain, appointed in early 1963. He was keen to have a station under the WWSSN scheme. However, USGS had committed all the stations globally. One of these was at Shillong, where I had assisted the USGS team in the installation and had learned all about it. Later, in November 1964, I joined CSIR-NGRI and was given the responsibility to set up a WWSSN-equivalent seismic station. This was achieved indigenously, and the station was activated on 11 December 1967 to record the aftershocks of the Koyna earthquake. This station has functioned efficiently since its installation not losing even a single day's record since its inception. Globally, this is the only station conforming to WWSSN specifications, not set up by USGS [1].

Discovery of a thick crust below Himalaya and Tibet Plateau region

The dispersion of Rayleigh and Love surface waves generated by the 25 August 1964 magnitude 6.1 earthquake located in the Arctic recorded at Seoul, Hong Kong, Shillong, New Delhi and Quetta was studied [2]. The entire path was continental. The waves recorded at Shillong, New Delhi and Quetta passed through the high Himalayan and Tibet Plateau region, while those recorded at Seoul and Hong Kong did not. The observed dispersion was compared with the 3-layer earth model theoretical dispersion curves. This resulted in the discovery of 65 to 70 km thick crust below the Himalayan and Tibet Plateau region. Later, controlled source seismic experiments conducted during 1980's and 1990's confirmed this finding.

Reservoir Triggered Seismicity (RTS)

Several anthropogenic activities, under favourable geological conditions, can trigger or induce earthquakes. These include filling of artificial water reservoirs, mining, geothermal energy production, natural

gas and oil production, injection of fluids for enhancing oil/gas recovery, etc. Among these anthropogenic activities, artificial water reservoirs triggered seismicity (RTS) is found to be the most prominent. The most damaging M 6.3 artificial water reservoir triggered earthquake occurred in Koyna, India on 10 December 1967, claiming over 200 human lives and causing widespread damage in the Koyna Township [3]. There are at least 4 other sites where RTS events exceeding magnitude 6 have occurred [4]. For the fear of triggering/inducing earthquakes, several anthropogenic activities had to be curtailed or stopped, such as the terminating construction of Auburn Dam in California, USA way back in 1970s. On 15 November 2017 the magnitude 5.5 Pohang earthquake in South Korea, which injured dozens and forced some 17,000 citizens to move to emergency housing, was found to be associated with a geothermal energy production project [5]. One of the latest examples is the fluid injection triggered magnitude 5.5 earthquakes in Oklahoma, USA, which resulted in curtailing/stopping of fluid injection for enhanced oil recovery. The 2 February 2024 magnitude 5.1 earthquake in Oklahoma, USA is also associated with disposal wells.

Very detailed analyses were carried out of all the cases of RTS globally. This led to developing criteria to discriminate artificial water reservoir triggered earthquakes from normal earthquakes, which have found a global application [6, 7].

We know precious little about the physical properties of rocks and fluids in the fault zones which host earthquakes. This is due to lack of nearfield observations. The study of triggered earthquakes in Koyna, India is providing valuable information about this most sought-after knowledge [8]. India published the first comprehensive book on RTS, 'Dams and Earthquakes' [4]. It was translated in Russian and Chinese languages in 1979 and 1980, respectively. An updated version, of 'Dams and Earthquakes', 'Reservoir Induced earthquakes' was published in 1992 [9]. Work at Koyna, India, including setting up of a network of 8 borehole seismic station, drilling of a 3 km deep Pilot Borehole near the Donachiwada Fault, that hosted the 1967 M 6.3 earthquake and several M ~5 earthquakes, for near field study of earthquakes has been reported in 'Reservoir Triggered Seismicity-Focus on Koyna, India' [5].

Low temperature thermal desalination

The first low-temperature thermal desalination (LTTD) plant was set up in Kavaratti, Lakshadweep in 2005. This is the first of its kind anywhere in the world and has been producing over 100,000 liters/day for the past 18 years. Kavaratti has a population of about 10,000 people. Consequently, the cases of water borne diseases dropped to less than

one-half in the subsequent years [10]. Moreover, the high nutrient cold water brought from a depth of ~400 m, when let out near the coast has enhanced fishing potential. In the following years several more LTTD plants were set up in other locations in Lakshadweep.

Indian Tsunami Early Warning System (ITEWS)

A magnitude Mw 9.2 earthquake occurred in Sumatra in the early morning of 26 December 2004. The tsunami created by it claimed over 250,000 human lives and is known to be the deadliest tsunami so far. At that time, what a tsunami is, was not known to the Indian public. 26 December was a Sunday, and people were having a leisurely walk on the Marina Beach in Chennai. When the trough of a tsunami reaches the coast, first the sea withdraws. And that is exactly what happened on the 26 December. People walking on the beach, not aware of a tsunami, just walked into emptied seashore to pick shells and fish. After about 15 minutes the crest of the tsunami arrived drowning thousands on the east coast of India. India took the initiative to set up the Indian Tsunami Early Warning System (ITEWS) and this was achieved in a record time of 30 months [11, 12]. It was discovered that there are only two sources in the Indian Ocean capable of generating tsunami. After a long discussion this was accepted by Inter-governmental Commission on Oceanography (IOC) in the 2005 meeting in Mauritius (April 14-16, 2005, http://ioc.unesco.org). The accepted Communiqué read *"Recognize the unique tectonic plate structure of the Indian Ocean, and that there are primarily two tsunamigenic sources that could affect the coastlines of the Indian Ocean, namely the Indonesian seismic zone and its extensions, about 4000 km in length, and the Makaran source"*. The unique feature of ITEWS is planting of the ocean bottom pressure recorders covering the two tsunamigenic-earthquake zones. This has helped in eliminating false alarm. ITEWS has been functioning well since September 2007 [13]. It is now considered to be among the best tsunami warning systems globally.

Antarctic scientific expedition

There are a few major Indian scientific programs that are of global importance. The Antarctica Program of the Ministry of Earth Sciences is one of them. Initiated in 1981, construction of Dakshin Gangotri, the first Indian wintering station in Antarctica, provided the foundation. This was achieved in the Antarctic summer of 1983/84, under the Leadership of Harsh Gupta. Having been built and populated in one Antarctic summer, it created a record, which still holds [14, 15]. This was achieved despite having a near fatal MI-8 helicopter crash on 29 December 1983, just on the third day after Finnpolaris ship's berthing in Antarctica on 27

December 1983. This enabled India to establish a strong global presence in Antarctic science and logistics.

Earthquake source multiplicity

Based on a detailed analysis of about 900 earthquakes that occurred during May 1968 and January 1971, a relation Ms =251.07 mb – 0.23 (between the surface wave magnitude (Ms) and the body wave magnitude (mb), was established [16]. The difference between the observed Ms and the one obtained corresponding to mb values provided a measure of source complexity. This publication formed a chapter in the Open University, text-book titled Geophysical Studies (Geophysics, Science: A Second Level Course, "Relationship between surface wave magnitude (Ms) and body wave magnitude (mb), pp 55-61, 1973).

Structure and tectonics in Himalaya and neighbourhood

The geo-data (seismic, geochemical, geological, thermal, Landsat imagery etc.) collected during the 1970's was synthesized to examine collision tectonics in the Himalaya [17]. Identification of low velocity layers was found to be consistent with the concept that the horizontal compression has been responsible for creating these weak zones and the inferred elevated temperatures in the vicinity of the Mohorovicic discontinuity below Tibet. Convergence of the Indian plate with Eurasia continues and is accommodated partly by crustal shortening and partly by lateral mass movement at the north-west and the north-east margins of the Indian plate. Shield like upper mantle's velocity structure was discovered below the Indo-Gangetic Plains [18]. Detailed investigation of seismotectonics of large earthquakes led to a conclusion that an M 8 earthquake could occur any time in the Himalayan region. However, there is no definite clue as to when and where it would occur [19].

Global Stress Map

An international effort was made to comprehend the global patterns of tectonic stresses. A team of scientists spread all over the world prepared the global stress map [20]. This study showed that most intra-plate regions are characterized primarily by compressional stress regimes. Extensional regimes are almost entirely limited to thermally uplifted regions. Mostly, in all plates, maximum horizontal stress is sub-parallel to the direction of absolute plate motion. This leads to the inference that the forces driving the plates also dominate the stress distribution in the plate interior.

Earthquake swarms precursory to earthquakes in North-east India

In a very detailed study of earthquakes in the northeast India region, where 10 earthquakes of M $\geq$ 7.5 occurred during 1897 through 1950, it was found that such earthquakes were preceded by well-defined earthquake swarms and periods of quiescence. The main-shock magnitude was related to the average magnitude of the largest two events in the swarm and the time interval between the start of the swarm and the main earthquake. Regression equations connecting these parameters were developed. It is important to recognize precursory swarm in real time. One such swarm was identified and a medium-term forecast was made which came true [21, 22]. The probability of an earthquake of M $\geq$ 7.5 occurring in the area and the time interval of prediction due to chance is 0.048 which is very small. Hence the occurrence of the forecasted earthquake can be considered to be significant. Incidentally, since 1950 Mw 8.7 Assam earthquake, the forecasted Mw 7.3 on 6 August 1988 is the largest earthquake to have occurred in the northeast India region.

Table 1: *Earthquake forecast for the northeast India region. Table provided the forecasted parameters and the earthquake occurrence details.*

Earthquake Prediction	Prediction Gupta and Singh, 1989	Occurrence NEIS
Epicenter	21°N – 25 1/2° N 93°E-96°E	25.116°N 95.171°E
Magnitude (M)	8 $\pm$ 1/2	7.3
Depth	100 $\pm$ 40 km	115 km
Time	Feb. 1986 - Dec. 1990	August 6, 1988 (00:36:26.9 G.C.T.)

Stable Continental Region (SCR) earthquakes

Major earthquakes in SCRs are rare. Only about 100 SCR earthquakes of magnitude exceeding 6.0 in the past 4 centuries occurred and, 10 of them were in India. Among these about a dozen had a documented surface rupture. Soil-helium surveys of the surface ruptures of two among these, namely the Koyna Mw 6.3 earthquake of 1967 and the Latur Mw 6.2 earthquake of 1993 [23], both in India, revealed propagation of the causative fault from the Archaean crystalline basement through the Deccan basalt cover. The first ever Chapman Conference in Asia was hosted at the CSIR-National Geophysical Research Institute, Hyderabad, from 25 to 29 January 1998, focusing on the Stable Continental Region (SCR) earthquakes. SCRs were significantly more vulnerable to earthquakes than once thought [24].

Gas hydrates studies

In studies spanning over the last 15 years [25], gas hydrate stability thickness maps were prepared for the Indian shelf, and locales with high potential of occurrence in Krishna-Godavari (KG), Mahanadi, Andaman, Kerala-Konkan and Saurashtra regions were identified using bottom simulating reflectors (BSRs). It was inferred that a large gas-hydrate energy resource within the Exclusive Economic Zone of India exists, and even 10% utilization of this resource could meet India's energy requirements for 100 years! The 9th International Methane Hydrates R&D Workshop "Science & Technology of Gas Hydrates: When can they be produced efficiently and safely" was held in 2014, which addressed all important issues connected with the production of Gas Hydrates, globally and specifically in India [26].

The success of test production at McKenzie Delta of Canada in 2007/2008, Alaska of USA in 2012 and in the Nankai Trough off Japan in 2013 faced the challenge of sand mitigation. Strengthening laboratory and simulation research is recommended to better understand gas hydrate dissociation kinetics and develop safe, cost-effective production technologies. Test production of the Qilian Mountains of China in 2016 over the permafrost regions and in South China Sea in 2017 provided great hopes for energy security of several Asia-Pacific countries like India, Japan, South Korea and China. Currently, in India, several organizations such as Oil and Natural Gas Corporation Ltd., Directorate General of Hydrocarbons, CSIR-NGRI, and CSIR-NIO are working on furthering the possible use of gas hydrates from the legal continental shelf of India.

Geothermal Energy

The potential of geothermal energy was underlined in the book entitled "Geothermal Resources: An Energy Alternative" [27]. In 2005 the first "Low Temperature Thermal Desalination Plant (LTTD)" at Kavaratti, India was installed. This 100 thousand liters/day capacity LTTD plant has worked un-interrupted for the past 14 years providing potable water to some 10,000 residents of Kavaratti. Consequently, the cases in hospitals in Kavaratti have dropped to about 40% as water borne diseases have been eradicated [10]. In the following years, similar plants have been set up elsewhere in Lakshadweep.

Demarcation of legal continental shelf

India in June 1995 ratified the United Nations Convention on the Law of the Sea (UNCLOS).

One of the first hugely successful Department of Ocean Development (DoD)/MOES program was to delineate outer limits of India's continental shelf. Data were acquired during 2002-2004. Program was led by NCAOR, NIO & NGRI. Forty Scientists and officials from 7 national organizations participated. A total of 31,000 line-km multichannel seismic reflection, gravity and magnetic data, bathymetric data along 42 pre-determined profiles in and off India's EEZ and deployment of 100 Ocean Bottom Seismometers was achieved. Data analyses and integration was carried by the National Centre for Antarctic and Ocean Research (NCAOR) Goa [28]. All this work was carried out in just three years' time (2002-2004). India has a land territory of ~3 million square km, and an exclusive economic zone of ~2 million square km. GOI, after review of the documents by a National Group of Experts, made its first partial submission on 9 May 2009 and could add ~0.6 million square km of legal continental shelf whenever its claims are accepted.

Developing an earthquake resilient society

From the hazard point of view, an earthquake of Mw ~8 could occur anywhere along the Himalayan arc. The 1905 Kangra earthquake of Mw 7.8 had claimed some 20,000 human lives. If such an earthquake occurs today, the lives lost could reach a million [29]. A year-long exercise was undertaken by the National Disaster Management Authority, India in the states of Himachal Pradesh, Punjab, Haryana and the Union Territory of Chandigarh involving the State and Central Government machinery, and the public in developing an earthquake resilient society. A mega mock drill was held on 13 February 2013 for a hypothetical Mw 8.0 earthquake occurring at 11 am near Mandi, to examine the effectiveness of preparedness to minimize the human lives loss as well as infrastructure damage due to the anticipated earthquake. The best part was the response of the public and it was clear that a lot has been achieved and more needs to be done. A similar exercise was repeated for the re-occurrence of the 1897 Shillong earthquake of Mw 8.3 in the year 2014 for the 8 northeast states of India [29]. The importance of observing an Earthquake Day has been underlined [30].

Encyclopedia of Solid Earth Geophysics

The Encyclopedia of Solid Earth Geophysics, published by Springer in 2011 had two volumes, 1539 pages [31]. It was very successful, with over 80,000 downloads by 2017. The popularity and the new work carried out necessitated bringing out the second edition of the encyclopedia in 2021, which has two volumes with 1950 pages [32].

Representation of Indian Earth Scientists in the concerned international organizations and related activities

India is credited with having 3 Presidents of the International Union of Geodesy Geophysics (IUGG), President of the Asia Oceania Geosciences Society (AOGS), Founder President of Asian Seismological Commission (ASC), besides several other important positions held. Among the important International Conferences held in India, the Asian Seismological Commissions biannual conference held in 1996; Joint Assembly of International Association of Hydrology (IAH) and International Association of Hydrological Sciences (IAHS) in 2009; Chapman Conference on Complexity and Extreme Events in Geosciences held in 2010; Asia Oceania Geosciences Society's Annual convention in 2010; Joint Assembly of IAGA and IASPEI in 2021 are outstanding events focusing on global issues and demonstrating India's contribution on salient issues. To commemorate 100 years of formation of the International Union of Geodesy and Geophysics (IUGG), INSA published a Thematic Issue entitled "Centennial Celebrations of the IUGG: Contributions from India" [33].

Concluding remarks

In the text, several geosciences related milestones since 1967, with which I have been associated, are briefly commented upon. In the following a few suggestions are made for the future geoscience related work in India.

1. Low-temperature thermal desalination: India has done very well by setting up LTTD plants in Lakshadweep. It is important to apply the same technique to convert high temperature wastewater of huge industrial setups like the fertilizer plants into potable water.
2. The excellent work carried out by the Department of Ocean Development (now Ministry of Earth Sciences) during 2002-2004 to identify that some 0.6 million square km area in oceans could be brought under India's jurisdiction, should be addressed with urgency.
3. The work carried out at Koyna, India, has demonstrated that focused research and observations using multi-disciplinary studies are likely to provide an answer to the questions facing seismologists all over the world as to what really happens before an earthquake is nucleated and how the rupture propagates. The RTS sites have easy access, and the seismicity is mostly limited to shallow depths of 2 to 10 km. If an artificial reservoir is built in a stable continental area, nearby earthquake sources do not interfere with understanding the

observed RTS. Therefore, these sites provide an excellent opportunity to carry out near-source studies. All efforts should be made to address earthquake nucleation related questions through observations at RTS sites. With the recent geotechnical and analytical developments, and the success of deep bore hole observations at SAFOD, USA, and Koyna, India, we appear to be close to comprehend earthquake nucleation and rupture propagation.

4. It is a fact that an M ~8 earthquake has not occurred in the Himalayan region since the 1952 M 8 aftershock of the great M 8.7 Assam earthquake of 1950. When and where such an earthquake will occur is difficult to forecast as of now. It has been estimated that occurrence of an M ~8 in the vicinity of Himalayas could claim several tens of thousands of human lives. Even if one tells that a magnitude 7 earthquake will occur in the vicinity of Delhi on the coming Sunday at 2 pm, can everyone leave Delhi? Therefore, we must learn to live with earthquakes. Following steps may be helpful:
    a. Observing an earthquake safety day in the vicinity of the Himalayan earthquake belt, like what is being done in Nepal on the 16 January of every year.
    b. Training of the school students about earthquake safety.
    c. Creating earthquake scenarios of the repeat of past M ~8 earthquakes and taking up preparatory phase of developing an earthquake resilient society, followed by mega-mock drills in other parts of the Himalayan earthquake belt, like the exercise conducted by NDMA for the 1897 and 1905 earthquakes.
5. India's global presence needs to be enhanced. The geographical national boundaries do not control geological features. Whatever is happening geologically worldwide affects India equally. It is important that the participation of Indian earth scientists is encouraged in the global forums. India has had a major role in global geoscience related programs. Just to mention a few: India has been deeply involved with Upper Mantle, Geodynamics, International Lithosphere Program, Planet Earth and Future Earth programs. The American Geophysical Union published volumes under Geodynamics Series from 1980 to 2003. The Volume 3 of this series was titled "Zargos-Hindu Kush-Himalaya: Geodynamic Evolution", which was much appreciated globally [34]. INSA had been regularly publishing progress reports of these programs, highlighting India's contributions. These programs included projects like Global Geo-Transacts, Global-Seismic Hazard Program (G-SHAP), Global Stress Map and many more. A very important program was the Science Plan on Hazards and Disasters

for the Asia-Pacific region, which produced two key reports: "On Earthquakes, Floods and Landslides" (http://www.icsu-asia-pacific.org/resourcecentre_hazard.htm) [35] and "The Special Vulnerability of Island Nations" (http://www.icsu-asia-pacific.org/resourcecentre_hazard.htm) [36]. India needs to support global geoscience-related programs, ensure the adequate participation of Indian Scientists in such programs, and host international geoscience-related meetings, conferences, and projects.

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Earth Science in India—Time Before and Time After[1]

Vinod K. Gaur

Scope

This article traces the evolution of Earth Sciences in India, emphasizing the establishment of key institutions and landmark discoveries in geology, geophysics, and seismology. It follows the trajectory of geoscientific surveys and academic initiatives before and after India's independence, leading to globally significant insights into Earth processes. These studies have established a lasting knowledge base that supports mineral exploration, hazard assessment, and the application of knowledge for economic benefits. The article advocates for future research to focus on an integrated study of the coupled geosphere-biosphere system, which evolves dynamically and gives rise to emergent phenomena that cannot be adequately understood through fragmented analysis of individual science domains.

The beginnings

Academic explorations of the Science of earth, began in India with the appointment in 1854, of Henry Benedict Medlicott, formerly of the British Geological Survey, as Professor of Geology at the then Thomason College of Civil Engineering at Roorkee. Whilst working closely with Thomas Oldham, the first superintendent of the Geological Survey of India (GSI), which had been established a few years earlier, Medlicott discovered the extraordinary sequence of sedimentary deposits in depressions of the oldest basements in east-central India. Similar occurrences of such formations of variegated fluvial and lacustrine facies, several kilometres in thickness, deposited under a few tens of millions of years of globally changing climate, were subsequently reported from five other continents. Their remarkable similarities of age and form, led Eduard Suess, a Professor of Geology at Vienna University, to propose the existence of a

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long-connected land mass. This was called **Gondwana land** to honour the culture of the region where it was first found.

Medlicott's discovery of the Gondwana series in the 1870s and its close correspondence with globally distributed formations of the same age, implied the operation of a yet to be discovered tectonic process leading to episodic assemblies and break-ups of large continents on earth. Three decades later, another discovery that would lay the foundations of modern seismology was made by Richard Oldham, the then superintendent of GSI. Diligently studying ground motion records generated by the M8.3 great Assam earthquake at other sites of the globe, he clearly identified the existence of the faster travelling longitudinal and the later arriving transverse waves, which had been theoretically predicted for elastic bodies a few years earlier. Concluding that the earth could be verily regarded as an elastic body in which earthquake wave energy can be regarded as being propagated along rays, he further interpreted the geographically delineated and spherically symmetrical shadow zone characterized by an absence of shear waves, as proof of the existence of a fluid core. Capable of advecting the outflowing latent heat released by the progressive solidification of material at the centre of the earth, the fluid core would later explain the mechanism of the geomagnetic dynamo.

Another seminal understanding of how planet earth dynamically supports elevated lands in the face of persistent erosion, iconized by the theory of Isostasy, came to light in the mid-nineteenth century from a prescient interpretation of the divergence between the directions of the vertical determined from star observations and independently, from an analysis of geodetic data. The latter had been generated by the Survey of India during the progress of the great Triangulation Survey (GTS) initiated in 1802 after the conquest of Mysore in 1799.

The GSI, established in 1851 like its earlier born twin, the Survey of India (SOI) in 1767, had been primarily instituted to serve the purposes of the colonial administration. The former was created to explore the mineral resources of the country, particularly coal reserves to fuel the expanding railway network that the British colonial government needed to govern the growing expanse of conquered territory following its victory in the 1757 battle of Plassey, and the latter to keep track of the land area for accurate revenue collection after the conquest of contiguous lands in southeastern India.

The aforementioned context of fundamental discoveries of global significance resulting from the establishment of politically motivated institutions in India, is a moving story of the unconquerable power of scientific passions. Colonel Lambton's proposal to the East India Company which resulted in the execution of the Great Triangulation

Project, persuasively argues for the availability of uniformly referenced accurate maps of a growing territory acquired by "our glorious conquests". It studiously avoids any mention of his basic motivation: to determine the ellipticity of the earth's oblate spheroidal shape, proposed by Sir Isaac Newton, from measurements of latitude intervals along a continuous chain of occupiable sites around the 78° from Kanya Kumari to Everest.

Thanks to such passions of science, the GSI under its first superintendent, Thomas Oldham, progressively widened its scope, despite a narrow mandate. Its officers drawn by the fascinatingly diverse terranes of the continent, began mapping their rock types, structures, age, and relationship to earth resources and earthquake hazards. Thomas Oldham himself, witnessing the frequent occurrence of small and moderate earthquakes in north-eastern India, started a project to compile the first catalogue of Indian earthquakes from the earliest times. These early foundations grew stronger with a continuous stream of documented research and memoirs that drew worldwide attention e.g., the discovery of Paleoproterozoic stromatolites in the Cuddappah basin reported by King in 1872, or the existence of a remarkable tectonic feature in northwestern Himalaya, mapped by D.N. Wadia in the 1920s, where an entire sequence of strata along with thrust sheets had been folded into a hairpin bend about a strong promontory of the under-thrusting Indian shield. Inevitably, the culture spread, proliferated and developed with the emergence of a growing number of academic university departments of Geology in the country, resulting in the construction of high-quality maps of India's varied terranes and their distinctive character, as well as a spurt in mineral exploration and mining. These knowledge products proved to be a valuable heritage for Independent India, set on a course of industrialization.

Earth science in independent India

Science of the earth was born as curious minds sought rational answers to explain the origin and processes that had created the wondrous wealth of the planet's heirlooms displayed in coastal cliffs, river valleys, mountain fastnesses and deserts. Thus, the sight of a stack of neatly stratified beds overlying the eroded surface of an older, almost vertically tilted stratified bed, exposed on an Edinburgh cliff, led the Scottish doctor James Hutton to deduce that contrary to the prevailing belief in Europe, planet Earth had a long history and was millions of years old. *Incidentally, the Hindu Cosmology states the age of the Earth to be 4.32 billion years (equal to one Brahma Day, (Srimad Bhagavatam, Canto 3, Chapter 11). Even as the way to its calculation remains obscure, we know that this number is intriguingly close, within 2.5%, to the value (4.543 billion ffl*

1%) determined by the disintegration rates of radioactive nuclei, which was discovered by the Physicist Henry Becquerel in 1896.

In his treatise on theory of the earth[2], that appeared in 1795 [2], Hutton argued that the sequence of long deposition followed by earth deformation, re-submergence, fresh deposition, and uplift, deduced from such exposures attested to the operation of a cyclic process in the Earth's history and, looking at their currently observed rates, to its deep time. Indeed, Hutton's rigorous mind considered it essential to state, at the very outset, the logical premise of his interpretation: "the forces and processes observable at the Earth's surface are the same that have shaped its landscape throughout natural history". This is the first explicit statement of the universal principle of symmetry of physical laws with respect to space and time, which was elevated to the status of an axiom as late as in 1905 by Einstein [3], in his paper, on the electrodynamics of moving bodies[3].

Our knowledge of the earth as exemplified by the above recounting, is thus advanced, essentially through serendipitously chanced upon, or imagination-driven investigations of phenomena operating in another space and time, and their logical interpretation or inverse modelling based on the universal laws of conservation and energy transformation.

Academic earth science departments in the country that numbered about 20 at the dawn of independence, continued to educate a limited number of graduates and researchers that would man the soon to be seeded earth resources industries, notably the construction of the Bhakra dam and the institution of Oil and Natural Gas Commission (ONGC), the National Mineral Development Corporation (NMDC), and later the Central Groundwater Board (CGWB). In time, their operations, opened up a host of earth science problems to be addressed and researched such as determination of active slip rates in the Himalaya as well as of rock stability parameters, to be factored in engineering designs of hydro-projects, development of ground probing systems for locating minerals and ground water and resource estimation methodologies and data analysis. The slowly growing number of earth scientists in the country got engaged in executing the works of these industries with a small number also researching the emerging issues and scientific questions, albeit under severe constraints imposed by lack of experimental facilities and analytical instruments. Earth science researches in post-war Europe were entering a vibrant development cycle of theory - experiment - theory around the 1950s, greatly stimulated by the trailing technologies for sensing and analysis left in the wake of the war effort.

On the other hand, Indian economy was struggling to revive after its disastrous bleeding since the 17th century. According to an authentic

report by William Digby, the British humanist journalist, 0.9 billion dollars was taken out of the country within a short period of 30 years between 1870 and 1900 AD. This was ineluctably reflected in the state of our educational institutions, impacting the opportunities available to young researchers to give effect to their imagination.

Earth science researches and explorations produce knowledge of the deep origin, and evolution of its resources and environment and, more importantly of its highly complex, bio-geo-chemical processes that determine their space–time characteristics. These knowledge products directly impact the economic health of a nation and thereby, its state of cultural and intellectual vibrancy. India's Golden Age of the Gupta period between the 3rd and 6th centuries, owed not a little to the production of a host of culture-embellishing objects wrought from a variety of earth resources, from clays and variegated textured rocks to ores and minerals. Will Durant, in his 1935 book [4], The Story of Civilization[4], records how the mining and metallurgical operations for winning metallic copper and iron, in that age, had reached a high level of accomplishment. The necessary knowledge needed for this accomplishment was gained by empirical logic rather than from a study of their fine structure that can now be gleaned through incisive analytical, probing and computational tools. But it testifies to the primal urge for seeking knowledge by logically mining it from whatever information is available. The engagement of seekers, investigators and practitioners in the 4th century India, hold us in awe by the quality of their pursuits.

As India's economy turned the corner in the 1990's, knowledge systems of the earth also grew steeply, not only quantitatively but also in sophistication, greatly stimulating imaginative research approaches to refine our understanding of the planet's bounties and paroxysms and to build community resilience against their possible adverse emergences.

High performance computational facilities and fine-resolution analytical instruments that bring an insightful understanding of a host of fine structure earth processes trackable by the space-time distribution of isotopes and trace elements in water bodies and soils, and radiation dosimetry that allows age determinations of geological and archaeological features, have created a substantially clear understanding of the structure of the epidermal layer of the earth that we live off. Substantial investments in creating a wide network of earth observing systems to record the dynamic state of both land and atmospheric variables, began to yield rich dividends in the form of reliable short-term weather forecasts and quantitative assessments of resource potential, as well as the anticipated intensities of natural hazards. In particular, the Earth System model [5] developed at the Indian Institute of Tropical Meteorology, designed to

capture both land surface and ocean bio-geochemical processes, is already proving to be a fairly dependable predictor of quantitative rates of change in the elemental composition of the atmosphere, biosphere and the hydrosphere and, thereby, future climates. The foregoing account is not intended to be exhaustive even as the few cited here have been selected to exemplify contributions that significantly advance our collective human understanding of planetary processes and phenomena.

The future

The scene is thus set for imagining an adventuresome future that would inspire and stimulate the new generation of earth scientists by the excitement of first principles science - the approach that revolutionized life science education and research in the country about a quarter century ago. It is rooted in the systems perspective of the coupled geosphere - biosphere earth system, which despite some intermediate-term cyclic behaviour, evolves dynamically, leading to emergent phenomena not derivable from the study of particular domains.

An instructive paradigm is to view the earth as a thermodynamically open system comprised of an interactive organization of five subsystems, powered by the heat flowing from its fiery interior and the daily radiation from the sun. The latter has created a wondrous world of hydro-biological ecosystems including the human, nestling between the solid earth and those characterised by the three phases of water. Each of these subsystems constantly exchanges matter and energy across transitional boundary layers, which are apparently structured in a specific manner to preserve their distinct identities. The characteristic structures of the animal cell boundary that preserve the internal configuration of its organelles even whilst exchanging matter and energy from its surroundings or that of the atmospheric boundary layer, strongly support the conjecture that boundary layers are specifically structured to channel the throughflows of matter and energy across them in a requisite manner that will sustain the specific organization of the system within. Accurate imaging of boundary layer structures, thus, promises to form a potentially illuminating window through which an insightful view of their interior structures may be gleaned

Deep seismic images of the earth reveal the existence of an inner solid core surrounded by 3 nearly spherical shells: the outer fluid core, the visco-elastic mantle and the substantially solid lithosphere. Each of these domains is separated from the other through a phase boundary across which material properties change drastically. Heat energy flows out radially from the hottest interior, that is the progressively solidifying inner core, traversing all three domains where the usable part of it is

transformed into kinetic energy in the manner of a thermodynamic engine; their forms determined by the allowable properties of their respective materials. Thus, is generated geo-dynamo in the outer core, mantle convection in the mantle and plate tectonics in the lithospheric shell resulting into new landforms on the surface [6]. Concomitantly, these processes, by redistributing materials within and on the surface, create nonspherical geometry of the earth's density distribution reflected in the global shape of its geoid and also of the manner in which the earth will ring when struck by a strong earthquake.

The heterogeneous structures in the boundary layers have been sculpted by the geographical distribution of heat flow streams across them and thermal characteristics of the intervening materials in the region controlled by the quantum mechanical principles of stability. Specifically, the Core-mantle boundary (CMB) layer has been shown to be characterized by higher temperatures, imaged through their low seismic velocity proxies, in two regions of its nearly spherical surface, one underlying Africa and the other under the Pacific. The inner core-outer core boundary, on the other hand, shows two colder regions on its surface, one beneath Asia and the other under the Atlantic. Logically, the higher temperature region on the CMB, predicating lower heat fluxes due to reduced gradient, will be expected to inhibit the heat fluxes flowing out of the inner core, thereby breaking the spherical symmetry of its freezing process.

Binod Srinivasan's recent study of convection in the outer core [6, 7] and the resulting magnetic regime by combining magneto-hydrodynamic theory and an amazing experimental design, suggests the existence of such an aspherical distribution of the inner core freezing, most likely conditioned by the CMB structure. If conditioning is imagined to entail some kind of communication between the two boundary layers, there arises an exciting possibility of exploring the form of this communication by studying their mutual entropy that may be hidden in the lattice structures of their materials.

The various thermodynamic earth engines taking the form of a geodynamo in the fluid core, viscoelastic mantle convection and plate tectonics, all generated in the wake of the outflowing latent heat from the inner core boundary are created by a shared throughflow of heat energy whose course is governed by the two principles of symmetry and transactional cost of energy transformation that govern all processes in the universe. These principles and their corollaries, notably the laws of conservation distilled from the principle of symmetry, are quantitatively expressed and therefore amenable to simulation on a computer. Indeed, several such computer simulated models now exist with considerable

scope for being modified to address a host of exciting questions related to imagined tectonic features created by the work of these geo-dynamic engines, e.g., the dynamics and consequences of plume ascents and inversely, determination with greater certainty, quantitative figures characterizing materials in the earth's graded pressure-temperature composition field, notably viscosity and density.

Development in earth sciences has closely followed new conceptual ideas in other fields, Newton's mechanics, Fourier's heat flow, radioactivity, Gibb's phase rules, fluid dynamics and several others. It has even worked the other way round: Hutton's postulate of the spacetime symmetry of Physical laws, was explicitly recognized by Physicists over a century later

Modern developments notably the Neutrino tomography of the earth can give us a direct estimate of density in various regions of the earth, as can free oscillation seismology, currently absent in India. Another significant light of great significance to understand deep earth mineralogy, is the formulation of the density functional theory which can be used to develop the exciting avenue of computational mineralogy with promise to energize both instructional and research endeavours.

Such are the opportunity spaces for earth science research and education in India with exciting prospects for adventuresome young academics and researchers to explore and develop, to keep the science vitalized through a rich cross-disciplinary perspective and in turn our syncretic civilizational uniqueness.

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VINOD K. GAUR is a natural scientist, curious to understand the wondrous display of the earth system's beautiful yet enigmatic phenomena and their inscrutable variabilities and, in particular, the deep earth processes that create them through an interplay with those powered by the sun's daily renewed energy.

Conscious of their complexity that has a possibility of being resolved only through a cross-disciplinary model woven with equations of mixed phase continuum mechanics, statistical and quantum mechanics and Information theory, he works closely with younger scientists inspired by their enthusiasm and adventuresome ideas.

V.K. Gaur is a passionate believer of the unified nature of creative works in Science, Arts, Music and Culture. This philosophy, implicit in the choice of his pursuits, also rules his worldview and lifestyle. Over a long career, he has worked as a University Professor, Institute Director, Secretary to the Government of India and back to being a Professor, experimenting with ideas and systems that looked potentially insightful and productive at each stage. Currently, he works as an honorary emeritus scientist at the CSIR-Fourth Paradigm Institute, in Bangalore, playing with mantle convection models and Physics infused Artificial Intelligence.

A particular conceptual obsession that occupies his reveries these days, interspersed with sessions of classical vocal music that he has now returned to after decades, is about the internal structures of phase boundaries in nature e.g., those of animal cells, the atmospheric boundary layer or those intervening the earth's fluid core and the visco-elastic mantle, and that between the outer fluid and the inner solid core. Since the boundaries separate two contrasting domains and help sustain their specific spatial configurations by mediating energy and material flows between them, they themselves must be specifically structured to channel these flows according to the heterogeneous requirements of the internally asymmetrical organization of these domains. Fine structure imaging of boundary layers, he argues, should therefore offer a most insightful window to understand the structure of the domains across them.

Some Thoughts on Meeting Challenges in Earth and Atmospheric Sciences in the Age of Artificial Intelligence

Archana Bhattacharyya

Scope

This article seeks to address a particular aspect of the broad theme of this legacy volume relating to challenges in a changing socio-techno-ecosystem, in the domain of Earth and Atmospheric Sciences. Undoubtedly, a major change in this ecosystem has been the arrival of 'Artificial Intelligence (AI)'. Among areas of Earth and Atmospheric sciences, where tangible returns from investments are expected, those related to exploration for minerals and energy, hydrology, and forecasting of natural hazards, are of great importance to society. In recent years, there has been a realization globally that AI can be harnessed usefully in these areas, particularly in view of the availability of large databases, realized from the widespread deployment of different kinds of instruments, which are also continuously improving their capabilities. In India also, in a few of these areas, some efforts to utilize AI techniques have begun. However, the advent of AI brings with it many challenges. Scientists working in specific fields are gearing up to meet specific challenges in their areas. Despite this there are some challenges of a general nature such as the role of basic research in the age of AI, advantages of a multi-disciplinary approach in the use of AI, issues related to data, and steps to be taken in education to keep pace with developments in AI, which require the attention of funding agencies for science and education in India. This article reflects on a few of those challenges in the Indian context, specific to Earth and Atmospheric sciences.

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Use of Artificial Intelligence in earth and atmospheric sciences

Globally there has been a widespread, though highly non-uniform, deployment of a plethora of instruments to measure an increasing number of parameters informing about the state of the Earth, its oceans, its mountains, its atmosphere, its ionosphere and its magnetosphere. The accuracy and resolution of these instruments have been increasing and this is buttressed by more uniform coverage of the globe by satellite-borne instruments. Consequently, vast amounts of observational data in the area of Earth and atmospheric sciences, including near-Earth space, is now available. The performance of computers we depend on to extract information from the data available to us, and build models, empirical or physics-based, has also improved substantially. The National Supercomputing Mission of the Department of Science and Technology, Government of India, is giving a boost to the country's computing power through the installation of indigenously assembled supercomputers in different institutions across the country (https://dst.gov.in/national-super-computing-mission). These supercomputers are equipped with applications, which may be useful in the areas of weather and climate research and computational fluid dynamics. However, India as a nation, continues to fall behind in the intellectual race in effectively using the available data and computational facilities, to pose and address important science questions, some of which are linked to the well-being of an increasingly technology-dependent society. For example, today the world critically depends on satellite-based navigation, communication, and remote sensing. The Global Navigation Satellite Systems (GNSS) and the Indian Regional Navigation Satellite System (IRNSS) not only provide us with accurate measurements of positions but also the current time with high accuracy. Availability of this information is now important for various forms of navigation and the time information is widely used to synchronise activities across infrastructure networks. Some events, which are elements of space weather, give rise to turbulence in the ionosphere, that can cause fluctuations or scintillations in the amplitude and phase of the received signals. Strong and rapid phase scintillations can cause receivers to lose their phase lock on incoming signals, thereby disrupting the reception of the signals [1]. The ionosphere over India is particularly vulnerable to the development of such turbulence because the ionospheric plasma here becomes unstable under certain conditions, which are common in certain seasons and especially when solar activity is close to its peak. However, there are several challenges in predicting ionospheric scintillations in low latitude (geomagnetic) regions [2]. It is therefore necessary for users of satellite-based navigation to have alternate means of navigation when such disruptions occur. In the case

of aircrafts, alternative would be the use of inertial navigation systems on board the aircrafts.

There are other important areas in Geosciences, where artificial intelligence (AI) techniques are being used in India. One such area is the identification of exploration targets in India for critical minerals and metals [3].

In Earth and atmospheric sciences (EAS), particularly for natural phenomena which can affect a large subset of the local population, a great deal of importance is attached to the development of forecasting models as, for instance, in the cases of earthquakes [4], monsoons [5] or space weather events that can affect satellites or satellite-based navigation, and that can give rise to geomagnetically induced currents [6, 7]. In each case, the related physical processes are complex and involve disparate spatial and temporal scales. This makes development of accurate models based on first principles thinking, untenable.

Large scale use of AI in different areas has now taken off in a manner that it is unlikely to take a back seat in scientific research. However, models created through the use of machine learning (ML) or deep learning (DL) algorithms and AI techniques, though may find extensive use by geoscientists, cannot be judged on the basis of their accuracy alone. In order to recognize patterns and arrive at the model, the AI technique has to be trained on a large data set. Therefore, besides the stability of the models and reliability of their accuracy, the question that has to be asked is whether they have the capacity for generalization to scenarios that have not been covered during their training [8]. Physics-informed ML models, incorporating domain knowledge, perform better in these aspects [9] and improve the interpretation of results [10]. Use of such models also reduces the amount of data and computing resources required to develop the model, which is important in the Indian context. AI-generated models have also been used to estimate the parameters required as inputs in a theoretical model, when such parameters are unavailable from direct observations. These considerations underline one of the major requirements for Indian groups to make useful scientific contributions, which is to use the big data scenario that EAS presents but at the same time ensure that basic research is not relegated to the background. Only a strong commitment to basic research will enable us to extract much more from the use of AI.

Need for multi-disciplinary approach

One of the advantages of deep learning methods is that they enable simultaneous processing of diverse sets of data, from a variety of sensors. The measured parameters often have vastly different sensitivities to

various characteristics of the system being modelled. These provide the grounds for the creation of highly nuanced models of a complex system. Complexities of the physical or chemical processes involved in the phenomena that contribute to the behaviour of the system call for a holistic approach and necessitate 'systems thinking' [11]. Therefore, synergistic team work among members with diverse expertise is the only way forward. This calls for investments in creating centres of interdisciplinary research at universities and other institutions in India, which not only create the human resource but also provide the environment for new science through synergistic collaborations among scientists with different expertise. EAS is particularly geared to the development of models utilizing big data. Use of AI algorithms to develop such models requires powerful computational resources, which is further reason for sharing such resources. Most of the challenging problems in Earth and Atmospheric Sciences today, need a team of scientists to take a holistic look at the problem. In many cases, these transcend international boundaries as well, because many of the problems are global in nature, or at least affect large swathes of the globe. It is necessary that funding in research recognizes this aspect of global nature of scientific research.

Issues related to data

The performance of supervised ML generated models depends on vast amounts of high-quality, labelled data. This brings in the importance of metadata, which is often overlooked during data acquisition and archival. For instance, there are five World Data Centres (WDCs) for Geomagnetism around the globe, which are members of the World Data System (WDS), an affiliated body of the International Science Council. The WDCs are repositories of digital geomagnetic data as well as indices of geomagnetic activity provided by a network of magnetic observatories distributed around the world. At some of the WDCs efforts have been made to include relevant metadata for each observatory. However, many observatories fail to provide important information such as the instruments that have been used to make the measurements during different periods. This is important as instruments used to make observations in magnetic observatories have been replaced, in the course of time, with better ones for improved accuracy and resolution. This fact creates a handicap in comparing data acquired over past decades with present day data. In 1991, the organisation INTERMAGNET was established to acquire geomagnetic data from a smaller subset of geomagnetic observatories that meet the requisite standards of instrumentation and data quality. Members of INTERMAGNET need to follow mandatory standards for measurement, data processing, formats and data transmission. At present, three Indian magnetic observatories are members of INTERMAGNET.

Today, some of the WDCs are working with the geomagnetism community and INTERMAGNET to improve the metadata associated with all the observatory data that is deposited with them. At present, many researchers in different areas of EAS do not make use of metadata, and may not be even aware of the role played by metadata in their discipline. Absence of properly curated and labelled data hampers the development of models using AI, where, generally, the focus is on constructing better algorithms. In this process, often the creation of standardized, properly curated data, is overlooked. Selection and pre-processing of a particular type of data requires expertise in that specific domain. In India, clearly, more effort is needed to establish standardized formats for metadata in different disciplines of EAS. Program Advisory Committees of Funding agencies have a role to play in advancing and adherence to this practice.

Researchers in AI/ML seeking to combine diverse data sets of different types, may often use data that have been sourced and archived by others. Diversity of data in EAS poses a major challenge to interoperability and reuse of the data, which is crucial for establishing reproducibility and transparency of the results. This has led to the establishment of guiding principles such as FAIR (findable, accessible, interoperable, and reusable) for the management of scientific data [12], which are accepted by the global Geosciences community. In India, now several government departments and institutions maintain data archives related to EAS. For example, the National Water Information System of the Ministry of Jal Shakti has created the India-Water Resources Information System (WRIS) for hydrological data, (https://indiawris.gov.in/wris/#/). The Data Hub and Analytics section of Bhuvan, the Geo-portal of the Indian Space Research Organisation, (https://bhuvan-app3.nrsc.gov.in/data/download/index.php), allows utilization of multi-sensor satellite data to conduct advanced analysis. Researchers in some areas of EAS should explore the utility of these data archives in the development of AI/ML models.

Education and public outreach

In geosciences, AI/ML model-based decisions are of critical importance to society. However, the more complex models lack transparency in that there is no explanation about how different factors influence the results. Explainable artificial intelligence (XAI) methods [13] are now being developed to provide the user, a glimpse into the 'black box' that AI techniques usually are. These methods aim to explain the importance of different factors in arriving at the model predictions. In the hierarchy of complexity of models, the simplest models are theoretical models based on fundamental concepts of the various processes involved. These

progressed from analytical models to numerical ones and provided the basis for developing more complex models for explaining observations. The idealized models have so far provided knowledge of underlying physical processes [14]. One reason why AI methods have not yet gained as much traction within the EAS community is that some proponents of AI within the community do not find it necessary to incorporate into AI, the existing quantitative knowledge about the physical processes provided by the idealized models. Another reason is the lack of formal training to geoscientists in acquiring AI skills. Just as idealized models are the essential building blocks for teaching the core subject to students, it is also necessary to introduce training courses, which provide adequate understanding of mathematical and computational techniques to enable geoscientists to make sensible and informed use of AI techniques, instead of blindly using easily available codes.

Development of improved scientific models for geophysical phenomena, particularly those that will be used in forecasting scenarios, must be accompanied by efforts to communicate the underlying science to the public. Building a bridge across the divide between science and society contributes towards enhancing public trust in science and the work done by scientists. This is particularly important for practical applications of the predictive capability of some of the scientific models in EAS, as the public learns to appreciate the probabilistic nature of the predictions. It is also widely recognized today, that public outreach of scientific organizations and institutions is of utmost importance to quell the promotion of misinformation through social media, especially given the capabilities of AI to make realistic videos based on imaginary data. In the present times, therefore, it is also important that our institutions for higher education impart some basic knowledge about how our planet has evolved over time and how it works as a physical system, to all the graduating students, no matter what their career goals are and what subjects they choose to study in their pursuit of these goals. This will create better informed citizens, who will be more acceptable of the public outreach efforts of EAS scientists.

Summary

In India, in the near future, one may see the use of AI to develop models for natural hazards such as tsunamis and landslides [15]. Undoubtedly, it is necessary to create an environment where Indian scientists working in different areas of EAS can derive maximum benefit from AI in developing models. To do so, certain overarching challenges that have to be taken care of are:

1. Creation of centres of interdisciplinary research at universities and other institutions, to foster an ecosystem of synergistic teamwork among members with diverse expertise, to tackle the complexities of different physical or chemical processes that contribute to the behaviour of the Earth system.
2. The practice of proper archival of data together with appropriate metadata, in accordance with FAIR principles, must be advanced by the Program Advisory Committees of Funding agencies, to create large, reliable, and accessible databases by scientists. Appropriate and frequent workshops to sensitise the researchers may be useful.
3. Strong commitment to basic research and emphasis on idealized models as building blocks in teaching students is required to incorporate existing quantitative knowledge about physical processes provided by the idealized models into AI. This will enhance trust in the models derived using AI.
4. Courses must be introduced to provide adequate understanding of mathematics, statistics, and computational techniques to enable scientists working in different areas of EAS to make sensible use of AI techniques instead of blindly using easily available codes.
5. Higher education institutions would need to impart some basic knowledge about how our planet has evolved and how it works as a physical system, uniformly to all the graduating students, no matter what subjects they choose to study in the pursuit of their career goals. This will create better-informed citizens, who will be more open to the public outreach efforts of EAS scientists. This will be essential for enhancing public trust in science and the scientists.

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State of Physics in India and INSA's Role

Sushanta Dattagupta

Scope

Keeping in view the circumstances behind the creation of Indian National Science Academy (INSA) in 1935, this article brings out the prevailing environment fifty years before Independence and the situation thereafter. Much of the discussion is centred around eight giants of Indian physics, four of whom worked during the three decades before the inception of INSA and the other four, afterwards. Their momentous contributions are used as paradigmatic suggestions for what needs to be done by INSA to improve the scientific scenario.

The Indian National Science Academy (INSA) has completed 90 years since its establishment in January, 1935. In this commemorative volume we shall attempt to bring out the salient features (i) briefly, about the history of Indian science, up to the late nineteenth century, (ii) over the three decades of the twentieth century just prior to the inception of INSA and the decade thereafter -- leading to India's independence, (iii) during the next 50 years of independent India, (iv) in the 25 years of this century, and finally, concerning upcoming prospects. In order to stay within the realm of my competence I will confine the discussion to Physics. We will also try to focus on "positive inputs" in relation to "the past, present and future of Indian science in a rapidly evolving global context", in accordance with the editorial guidelines. However, in order to discuss "the past", it is contextual to make a few statements on the circumstances around the formation of INSA, which started its journey under the epithet: National Institute of Sciences with an Englishman Lewis Fermor as its first President. Our assessment will be limited to work done from India on *basic physics and by physicists who are no more*.

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A brief history

India is credited to have had one of the oldest universities of the world — in Nalanda (5^{th}–12^{th} century AD). Nalanda was based on indigenous values and philosophy, derived out of Buddhism. It was truly an international university catering to all areas of education, including science and was a meeting place of scholars from far and wide. Buddhism does not believe in the caste system and gave recognition to people working with their hands. The decline of Buddhism thus saw increasing neglect of hands-on experiments. Thereafter, India stayed focused only on 'high thinking' – in astronomy and mathematics -- thereby we lost out on industrial revolution and the concomitant upsurge of science that took place in Europe.

After Nalanda was demolished, it appeared that we went into a slumber for nearly 800 years until the British established three universities in 1857 — in Calcutta, Madras and Bombay. Along with these universities were created Asiatic Society, Science Congress Association, Indian Museum and a slew of Surveys. Incidentally, Fermor, the first President of INSA was Director General of the Geological Survey of India. It is not surprising that these institutions were all located in Calcutta, then-capital of British government. The British also encouraged progressive thinkers like William Jones, William Carey, Lord Bethune, David Hare, … , who in turn, helped nucleate the reform movement of Rammohan Roy, H.L.V. Derozio, Ishwar Chandra Vidyasagar and others. In this atmosphere of the so-called Bengal renaissance came Asia's first research institute: Indian Association for the Cultivation of Science (IACS) in 1876, at the initiative of a private medical practitioner Mahendra Lal Sircar and a Belgian Jesuit priest Eugene Lafont, a teacher then at St. Xavier's College, Calcutta wherein he had established the first science laboratory of modern India. I make a special mention of IACS here because of its close connection with the founders of India's three national academies including INSA: C.V. Raman and Meghnad Saha.

Three decades prior to formation of INSA

INSA came into existence in 1935 in footsteps of quantum revolution in the first three decades of the twentieth century which George Gamow dubbed "*Thirty years that shook physics*". In this climate, a mentee of Father Lafont, who can be considered as India's first modern experimental physicist — Jagadis Chandra Bose — was working in Presidency College, Calcutta. Around 1895 Bose was busy demonstrating how to transmit electromagnetic waves in a wireless mode. Recall that this was two years before the discovery by J.J. Thompson of the electron and five years prior to advent of quantum theory due to Max Planck. J.C. Bose later

turned his attention to how electromagnetism influences matter: living and non-living, such as metals and an array of plants. In relation to his study of response of non-living matter to electromagnetic radiation (and also mechanical stress) Bose had anticipated what quantum mechanics theorized — that all material objects are constituted of atoms and molecules which vibrate even at zero temperature. As INSA is striving to put India on the world map of science, in which quantum mechanics is playing a leading role, it is pertinent to cite J.C. Bose, who was an influential teacher of M.N. Saha, a co-founder of INSA.

Very briefly, Gamow's "thirty years" began in 1900 when Planck gave his radiation law that describes how the energy density of blackbody radiation behaves as a function of the ratio of radiation frequency to temperature of the enclosure. This required a revolutionary hypothesis that the walls of the enclosure radiate back energy in *discrete* packets. Albert Einstein then gave a concrete formulation of these energy packets in 1905 in terms of what were called "light quanta" and rederived the Planck formula from the hypothesis on entropy by Ludwig Boltzmann. While this aspect of quantum mechanics had to deal with radiation, a few years later in 1911-13, Niels Bohr and Arnold Sommerfeld proposed that electrons inside an atom, say hydrogen, do not move in continuous paths but in discrete elliptical orbits and when they transit from one orbit to another, spectral lines are seen.

It is this facet of electron trajectory and consequent spectral emission that goaded M.N. Saha in 1919-20 to carefully examine ionized gases in stellar atmosphere. Because of high temperature, the atoms are stripped of their electrons leading to a gaseous plasma and these ions recombine to yield radiation, which Saha proposed to study in the laboratory. The ensuing ionization formula that he derived enabled a scheme to measure the temperature of stars. INSA is fortunate to have had M.N. Saha as its second President (1937–39).

Satyendra Nath Bose, a classmate of Saha and also a pupil of J.C. Bose, was grappling with a 'proper' derivation of the Planck radiation formula while he was teaching at Calcutta and then Dacca University. In 1924 he wrote from Dacca to Einstein explaining his thoughts on why light quanta being indistinguishable entities have therefore to be counted differently from classical particles. This led to the foundation of Bose-Einstein statistics, and Bose-Einstein condensation, two cornerstones of quantum theory. Incidentally, the year 2024 was celebrated as the centenary of quantum mechanics, counting hundred years from the date Bose wrote that famous letter to Einstein. S.N. Bose was elected President of INSA (1949–50).

We now come to Chandrasekhara Venkata Raman. Raman, working in IACS and Calcutta University, got interested in the scattering of light by liquid molecules, along with his distinguished student Kariamanikkam Srinivasa Krishnan. On 28 February 2028, celebrated as National Science Day, Raman announced his observation of the change of wavelength due to inelastic scattering of light. This work, which fetched him Asia's first Nobel Prize in physics in 1930, illuminated the quantum behaviour of molecular vibrations influenced by the impinging radiation. Raman founded the Indian Academy of Sciences in Bangalore in 1934, which has a symbiotic relation with INSA, especially in the context of outreach in science education.

Thus, all contributions by the doyens of Indian physics — J.C. Bose, C.V. Raman, M.N. Saha and S.N. Bose — were connected to electromagnetic radiation, and all around 'The thirty years that shook Physics'. Interestingly, J.C. Bose and C.V. Raman were first rate laboratory scientists while the interests of S.N. Bose and M.N. Saha were also shaped by experimental physics. Raman did receive the coveted prize, but arguably, all the other three were worthy candidates. It is this background of patriotic fervor — that natives were no less competent to carry out worldclass research — which contributed to the genesis of INSA to put Indian science into the international arena.

The next decade of 1930's witnessed application of quantum theory to chemical bonding, spectroscopy, magnetism, etc. One pioneer in this area, especially in experiments on anisotropic crystal magnetism, was K.S. Krishnan at IACS. Magnetism, dealing with either the intrinsic electronic spin yielding para magnetism or electronic orbital motion leading to diamagnetism, is essentially a quantum phenomenon. The torque method devised by Krishnan in 1935-36 to measure anisotropic susceptibility, earned him an international reputation. It is pertinent to note that Krishnan also adorned the chair of INSA during 1953-54.

First fifty years of independent India

The post-independent India saw the growth of a plethora of scientific agencies and laboratories under governmental departments. Thus, Physics got an enormous boost from the creation of the Department of Atomic Energy, Indian Space Research Organization, Council of Scientific and Industrial Research and Indian Statistical Institute. There are other contributions in this special volume by experts on these Agency-driven research efforts and I shall therefore refrain from making further remarks, except to point out that all the laboratories mentioned above were developed outside the university system. Has this led to positive outcomes for basic science? We shall return to this aspect later.

Along with establishments of various department-sponsored research activities, independent India also experienced impressive creation of Institutes of Technology (IIT) — at Kharagpur, Kanpur, Madras, Bombay, Delhi and Guwahati. Many of the IITs had lively physics departments but, it is fair to stress that the emphasis in IITs was on engineering and technology. In addition to IIT's new central universities that came into existence — Jawaharlal Nehru University, New Delhi in 1969, North-Eastern Hill University, Shillong in 1973, University of Hyderabad in 1974 and later, Pondicherry University in 1985. The synergy between teaching and research got a further boost *via* the creation of these centrally funded universities.

While we would go back to the issue of the Agency-University divide, we return to times right after our independence when the legacies of top-grade theoretical research by stalwarts like M.N. Saha and S.N. Bose and exemplary experimental work by C.V. Raman still pervaded the Indian landscape. In this background a young man, completely self-driven: Amal Kumar Raychaudhury (AKR), was working on his own at IACS, Calcutta, on Einstein's revolutionary work on General Theory of Relativity (GTR) that invokes curved space-time geometry for dealing with the weakest of Nature's forces viz., gravitation. AKR, as he was known to his students, was busy applying GTR to cosmology in 1955 and in what came to be called 'Raychaudhury Equation' which is a crucial component in the derivation of singularity theorems in GTR. AKR joined Presidency College in 1961 and served as a revered teacher of physics for close to two decades.

As far as Raman's legacy is concerned, mention must be made of Sivaramakrishnan Pancharatnam. Under Raman's directions, Pancharatnam was experimenting on optics. It was known by that time — from equations of electrodynamics by James Clerk Maxwell (1860) and special theory of relativity by Einstein (1905) — that light or electromagnetic radiation is a transverse wave and has two states of polarization in a plane normal to its propagation. Pancharatnam discovered in 1956 an intriguing phase relation between these two states of polarization by making polarized light pass through a crystal. The resultant phase was rediscovered – in the realm of quantum mechanics, wherein wave-particle duality works – and rechristened as *geometric phase* by Michael Berry, in 1983. During his very short lifespan Pancharatnam taught physics at Mysore University.

Another disciple of Raman, Gopalasamudram Narayana Iyer Ramachandran, took up diffuse X-ray scattering for investigation of crystal optics at Indian Institute of Science (IISc), Bangalore. His focus however was on biochemistry of peptides. The 'Ramachandran Plot'

that he discovered in 1963 provided a novel way to visualize structures of proteins. He also devised a triple helical model of collagens.

By now we have covered six decades of Indian Physics with INSA (1935) juxtaposed right in the middle. In the three decades before the inception of INSA we talked about J.C. Bose, C.V. Raman, M.N. Saha and S.N. Bose, and in the following three decades: K.S. Krishnan, A.K. Raychaudhury, S. Pancharatnam and G.N. Ramachandran. What are the common attributes of these eight pillars of Indian Physics? I list them below.

1. All made internationally acclaimed contributions *from India* that led to distinct schools of thought in the world over. (a) Marconi, who had seen J.C. Bose's setup, extended microwave transmission to the region of radio waves and got the Nobel Prize. For his detectors, JCB used semiconductors about which Neville Mott had said: "Bose was ahead of his time by at least sixty years". The crescograph that he had designed to measure plant response found universal acceptance. (b) Raman, of course, was well-recognized through the Nobel Prize "for his work on scattering of light and for the discovery of the effect named after him". (c) M.N. Saha's work on thermal ionization and the effect of radiation pressure on ionosphere and stratosphere is considered to be the harbinger of modern astrophysics. (d) S.N. Bose's new counting method based on indistinguishability of photons gave rise to new quantum statistics and his research had germinated several Nobel prizes in physics later. (e) Apart from his strong involvement with discovery of the Raman Effect, Krishnan's torque technique to measure magnetic susceptibility was widely used by the Cambridge University experimentalists for measuring magnetic oscillations in low-temperature diamagnetism. (f) AKR's work had implications for gravitational collapse to a blackhole and the Big Bang origin of the Universe, which further led to enunciation of the famous 'Singularity Theorems' by Roger Penrose and Stephen Hawking. (g) Today, in the active field of so-called topological systems, the Pancharatnam-Berry phase plays a crucial role. (h) The 'Ramachandran algorithm' is a forerunner of the algorithm used in CAT scans. For his work on crystal physics and other important contributions in related fields, Ramachandran was honored by the prestigious Ewald Prize of the International Union of Crystallography, in 1999.
2. All were researchers as well as teachers, in Colleges and Universities. (a) JCB taught in Presidency College. (b) Raman taught in Calcutta University and IISc. (c) Saha was a teacher at Calcutta and Allahabad Universities and authored several excellent text books on Thermodynamics. (d) SNB was a teacher at Calcutta and

Dacca Universities. (e) Krishnan taught at Dacca and Allahabad Universities. (f) AKR is known to have inspired a generation of students of Presidency College for taking up physics as a career option. (g) Pancharatnam briefly taught at Mysore University. (h) The Molecular Biophysics Unit at IISc was set up by Ramachandran after he left his teaching position at University of Madras.

3. The majority of these great sons of India had their research characterized by inter-disciplinarity. (a) Recall that J.C. Bose's initial interest was in electromagnetic communication, especially in the microwave domain. Later, he switched his interest from physics to plant science. Indeed, Bose is regarded as the father of modern biophysics in India. (b) Raman Spectroscopy is truly an interdisciplinary tool for physicists, chemists and biologists. (c) Saha's ionization equation for ratio of ionic concentrations in terms of ratio of partition functions had signatures of the Eyring-Polanyi equation in chemical kinetics that came later. (d) The Bose-Einstein Statistics (and the complementary Fermi-Dirac Statistics) are fundamental to all quantum phenomena in basic sciences. (e) Krishnan's work on crystal fields and magnetism permeate to realms of both chemistry and physics. (f) What Pancharatnam phase revealed that it is a general occurrence for adiabatic cyclic processes in the parameter space of the Hamiltonian, like the Longuet-Higgins phase in molecular systems (1958) and the Berry phase in topological solid. (g) Finally, Ramachandran, employing techniques of diffuse X-rays, actually studied problems in biochemistry and biophysics. In fact, in the era in which these individuals worked, physics and chemistry were not partitioned into separate disciplines as they are today. It is perhaps amusing to note that the name "photon" for light quantum was coined by Gilbert Newton Lewis in 1926, who is otherwise classified as a physical chemist.

4. Barring Saha, Bose and Raychaudhury, all five were experimentalists. Even Saha was partly an experimentalist, as seen in his work with Allahabad student M.M. Joshi, thus underscoring the fact that it is the laboratories which drive theoretical research.

5. All of them believed in India as one nation. Therefore, inter-state and inter-institution mobility was not viewed by them as exceptional. Raman came all the way from Madras to Calcutta and then settled in Bangalore. Saha, born in Dacca, came to study and work in Calcutta, moved to Allahabad and then back to Calcutta. S.N. Bose transited from Calcutta to Dacca where he worked for close to twenty-five years. Krishnan's example is even more striking — he came from Madras to Calcutta to do his PhD under Raman's guidance, then took up a

job at Dacca, returned to Calcutta, again moved to Allahabad and finally, to Delhi.

Following Ramachandran's famous contribution in 1963, the last century witnessed almost three and a half decades of hectic activities, but mostly around research institutes. We are not mentioning any individual here in line with our stated premise that only deceased physicists who had done their best piece of work from India find their names here.

Twenty-first century and outlook for future

The present century has seen further expansion of institutions — several more IITs and Central Universities were added to the list. A new important advent in an effort to promote basic sciences and integrate bachelor's and master's curricula came in the form of Indian Institutes of Science Education and Research (IISER) in 2006. A separate write-up on IISERs will feature in this volume to which the reader's attention is directed.

I now devote the rest of my article by raising a few questions, in the background of the exemplary instances of eight physicists mentioned earlier.

1. Why has India not produced experimental physicists of the same calibre despite the establishment of so many research institutions?
2. Notwithstanding our stated position in not mentioning individuals who are alive today, the fact remains that very few theorists have come close to Bose and Saha — why?
3. What can be INSA's role in mitigating these gaps?

I do not have easy answers to the first two questions, but I can try to proffer my suggestions on what INSA can do.

1. All eight scientists mentioned above worked in university departments in India, yet maintaining close linkages with western science. It goes without saying that basic research and teaching are two sides of the same coin — one complements and supplements the other. In this connection, it is worth recalling that S.N. Bose was harangued by his students in Calcutta and Dacca universities, wanting to know how the Planck radiation formula was derived. It is this constant inquisitiveness from students that nucleates new breakthroughs in research. This is also the case in all western efforts where path-breaking research has emanated from universities, which provide the necessary forum for diffusion and dissemination of knowledge, in an atmosphere of free, unbounded thinking. INSA ought to make an earnest effort to bring back the past glory and unshackled functioning

of Indian universities. Here I can cite the example of Banaras Hindu University (BHU). Many of India's very successful scientists in all fields had an association with BHU — before independence and for two decades thereafter. They came from all parts of India, either as students or as faculty and got enriched by the liberal atmosphere of the university campus.

2. In today's world, the partitioning of departments is meaningless. Take, for example low-dimensional carbon materials, namely fullerene, graphene, etc., which have bagged a couple of Nobel prizes for their exotic properties and applications of their quantum attributes. Now, the entire foundation of these materials rests on the valency structure of a single carbon atom. This aspect, related orbital configurations and the consequent bonding are usually taught in chemistry courses. However, when solids are formed, one needs techniques of reciprocal lattices, many body physics, etc., which are normally in the domain of physics syllabi. One other example is photosynthesis — sunlight helps chlorophyll molecules in tree leaves to soak CO_2 from air and, by chemical reaction, to yield oxygen, essential for our existence. Now, the influence of sunlight is to trigger an electron transfer process that requires quantum mechanics for a proper understanding. Thus, photosynthesis combines the disciplines of plant science, chemistry and physics. INSA needs to formulate a well-articulated document to promote interdisciplinarity in our undergraduate curriculum.

3. INSA has to find ways to improve the dismal state of laboratories in our colleges and universities, the reason perhaps being inadequate funding, not to mention that gross spending in Research and Development, in general, has declined to way below the world average. In spite of so many relatively well-funded and better orchestrated organisations, very few places have attractive post-doctoral possibilities. The institute-university divide and the consequent lopsided funding have driven brighter students away from universities because of deteriorating laboratory, library and hostel conditions. Can INSA not recommend ways of making more inter-university centres such as the one on Astronomy and Astrophysics at Pune, the Indore Centre in proximity to the synchrotron facility of Atomic Energy and the Accelerator Center at New Delhi? Like the Max Planck Institutes in Germany, whose directors are also Professors in adjoining universities, this will go some way in cementing the bond between universities and research centers.

4. It is important to make basic science-teaching exciting and counter the negative societal perception of engineering streams to be the first option for students after high school. The mushrooming of coaching

centres has further exacerbated the problem and has made education a corporate-driven business enterprise. INSA has its task cut out to address this issue.

5. INSA can try to help improve the declining trend of mobility of students from one region of the country to another. This needs better infrastructures in universities, as stated before and scholarships for outstation students. The situation has not been helped by making Education as a "Concurrent" subject of the Indian Constitution, leading to State *vs* Centre conflicts and inevitable politicization.
6. English is no longer viewed as a language of colonial masters; it has become the universal language of science communication, the world over. Germany and France, which are known as quite chauvinistic about their respective languages, have turned to English as a medium for their scientific journals. India had a special advantage in being conversant with English over other Asian nations, in particular. But this advantage is being discernibly withered away in recent times, especially amongst young Indian students, perhaps again due to political biases. Can INSA make an effort to revive English, especially in high school teaching of science?

Today, India and the world at large are engrossed with quantum technology in the form of quantum information, quantum computing, artificial intelligence, etc. The foregoing analysis is meant to assert that such efforts will only succeed if the base of knowledge is strengthened through revamping of university teaching. In conclusion, therefore, it is our fervent hope that INSA will make all attempts to help the country usher into its days of glorious tradition.

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Equation-based Knowledge Construction in Earth Science

R.N. Singh

Scope

Humanity needs reliable knowledge of Earth's behaviour, as our survival hinges on our ability to understand and adapt to it. The Earth continues to evolve in its structure, properties and processes. As our understanding of natural laws evolved, their applications have made our knowledge of the Earth system increasingly robust and quantitative. The language of natural laws is expressed through various forms of partial differential equations and their approximations. The standard methodology in geosciences is to compare the solutions of such equations with observations, and from this comparison, infer the properties and processes operating within and on the surface of the Earth. In India, organized efforts in this direction began with the establishment of the Theoretical Geophysics Division in 1963 at the National Geophysical Research Institute (CSIR-NGRI), Hyderabad. Originally, analytical tools were used for their solutions, and these were followed by computing. How such activities would change in the current era of artificial intelligence and a changing landscape of various Earth science applications is discussed.

Introduction

Earth science knowledge can be categorized primarily as knowledge of Earth objects of sizes ranging from the Earth system to mineral grains or Earth processes as fast as earthquakes and as slow as heat conduction in the crust. As all Earth objects evolve and never remain the same with time, many Earth scientists focus more on Earth processes to understand Earth's behaviour. Understanding of processes is analyzed in terms of cause-and-effect relationships. Earth scientists use natural laws to quantify cause-effect relationships. This is done with the help

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of relevant mathematical equations constrained by observations. Earth science has benefitted tremendously from observations made on Earth, in space and in boreholes and experiments in laboratories under various environmental conditions, yet nature's equations have been central in deriving reliable knowledge constrained by these observations. Such Earth science knowledge goes into providing minerals to us, in ameliorating natural hazards and also discussing role and future of our existence on Earth.

In general, Earth science knowledge is created either using data-driven thinking or through equation-driven thinking. In India, equation based thinking in Earth science started in a more organized manner at NGRI. In its wisdom, the institute created a Division of Theoretical Geophysics in 1963 and perhaps this was the first department of its kind anywhere in the world. It was fashioned as department of theoretical physics elsewhere.

It was realized that all problems of Earth science can be reduced to following three grand classical equations for fields denoted by f, time denoted by t as [1]:

$$\nabla^2 f = 0 \qquad \ldots\ldots\ldots \quad (1)$$

$$\nabla^2 f = a\frac{\partial f}{\partial t} \qquad \ldots\ldots\ldots \quad (2)$$

$$\nabla^2 f = b\frac{\partial^2 f}{\partial t^2} \qquad \ldots\ldots\ldots \quad (3)$$

The physical properties are represented by parameters (a,b). ∇^2 is Laplacian in spatial coordinates. Equation (1), called Laplace equation, is useful for interpreting potential field data such as gravity, magnetic, porous and viscous fields. Equation (2), called diffusion equation is useful for interpreting diffusion of heat, long period electromagnetic and pollution distribution fields. Last equation (3), called wave equation, is useful for interpreting acoustic, elastic and electromagnetic waves in the Earth.

As an example equations based on natural laws of fluid motion were used to investigate questions like origin of Earth's magnetic field due to likely dynamo action in the Earth's core and onset of thermal convection in the mantle. In the past, there were few geophysical sensors by which one could collect only an 'ounce' of data, so the group at NGRI relied on a 'pound' of equations to design geophysical techniques to explore geological bodies and to provide understanding of Earth processes.

Such knowledge will be reliable and will also survive longer than the knowledge, just based on the data alone. We quote Albert Einstein in support: "*One must divide one's time between politics and equations. But our equations are much more important to me, because politics is for the present, while our equations are for eternity*." Some such applications will be described in the sequel.

Earth structure

A theoretical problem which attracted the attention of a large number of NGRI scientists in 1960s and 70s was so so-called overburden effect. As our land falls in the tropics, its surface is highly weathered. Thus, all the desired ore bodies are hidden under an inhomogeneous layer. NGRI scientists focused on the diffusion equation for induced magnetic fields in designing electromagnetic exploration methods (on land and boreholes) to delineate the electrical structure of the subsurface using the following equation where magnetic field, electrical conductivity and permeability of free space are denoted respectively by by $\vec{B}$,σ, & μ_0:

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \vec{B} \qquad \text{.....} \qquad (4)$$

As the electrical conductivity of subsurface rocks varies over a wide range, such methods provide excellent discrimination between varied types of ore bodies. Responses of large types of idealized orebodies were computed. These solutions were also tested in analogue models of laboratory simulations and applied to field conditions. These studies were motivated by the desire to understand special geological conditions of the Indian region. Electromagnetic and seismic fields were calculated for stratified and anisotropic layered models for applications to crustal structure studies.

Earth processes

Numerous tectonic features of Earth are produced by redistribution of thermal energy in the Earth. Emplacement of ore bodies, uplift and erosion of Earth surface, orogenesis, metamorphism and sedimentary basin formation, all involve transport of heat. The heat conduction equation is similar to scalar version of magnetic diffusion equation for temperature (T), with density (ρ), heat capacity (C), thermal conductivity (K) and radiogenic heat (A):

$$\rho C \frac{\partial T}{\partial t} = \nabla . (K \nabla T) + A(r, t) \qquad \text{.....} \qquad (5)$$

Application of this equation to problems in tectonics became possible as surface heat flow and heat generation values were extensively measured at NGRI. To begin with, very simple thermal models of crust and moho temperatures were developed. Heat conduction models excluded effects such as nonlinearity and heterogeneities. The first effort was to introduce nonlinear model of thermal conductivity. Using radiogenic heat distribution model (step and exponential-type models) Moho temperature was found to be much higher than other shield regions. Linear heat flow-heat generation relationship was also predicted by basing it on heat conduction theory. An interesting way of predicting this relationship came about by the use of variational methods based on the rate of entropy production. Research studies were also directed to theoretically examine as to how survival of such a linear heat flow and heat generation relationship is possible under cases of differential erosion and uplift.

Rheological laws of minerals like olivine, developed using experimental methods, were combined with thermal model to develop rheological model of the crust by partitioning it into brittle and ductile regions. Application of this approach to Indian region brought out the changes in the thickness of brittle layer in northern Indian region. This result also explained vertical distribution of seismicity and the high thickness of the Himalayan crust due to crustal doubling. This approach also provided a pioneering prediction of the thickness of thermal lithosphere in the northern region to be about 100 km.

Heat conduction theory has been also used in interpreting the observed pressure and temperature data in Dharwar craton. It needed to infer the nature of heat generation model of the then crust, which has since been eroded to expose, the then deeper rocks. In order to increase depth (i.e. pressure) without the addition of any radiogenic heat in upper regions, outpouring of massive amount of basalt with low radioactivity was considered. This was proposed earlier in the context of cratonic evolution elsewhere. This idea helped find thermal structure and moho heat flow at that paleo-time.

Using a parametrized model of mantle convection, the manner of the cooling of mantle under south India through geological time was estimated. Complex moving boundary problems of lithosphere were constrained using heat conduction theory with nonlinear boundary conditions. Heat conduction theory with the addition of fluid advection, advection-diffusion model, help interpret paleogeotherms that determine metamorphism in the southern Indian terrain.

The Indian region abounds with sedimentary basins. An understanding of their evolution requires the use of heat conduction and flexure of

elastic plates theories. The plate flexure equation comprises horizontal distance (x), depression (w), load (q), flexure rigidity (G) and in-plane compression (P):

$$D\frac{d^4w}{dx^4} = q(x) - P\frac{d^2w}{dx^2} \quad \text{.....} \quad (6)$$

The question here was the nature of the heat source from deeper Earth to transform the unstable gabbro rock column into eclogite of higher density. This higher density rock then pulled down the surface to form a basin with deposition of over 7 km thickness in Cuddapah basin. Formation of such a thick basin cannot be explained by postulating a heat source leading to uplift of surface by thermal expansion process and followed by erosion. Such a mechanism is good only for thin sedimentary basins. Flexure equation has also been used to explain various topographic features of Indian ocean in combination with joint analysis of gravity and bathymetry data to estimate isostatic compensation mechanisms of topographic features revealing the tectonics of the region.

Heat conduction theory can also be applied on groundwater modeling. This problem of modeling of water table dynamics also requires the use of nonlinear diffusion equation:

$$c\frac{\partial h}{\partial t} = K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + I(x,t) \quad \text{.....} \quad (7)$$

where, h is thickness of aquifer, t is time, c is the storage, K is hydraulic conductivity and I is the recharge. This diffusion framework after linearization was used for time dependent recharge, stream-water table interaction, sloping aquifers, stochastic effects and many more problems.

Transport of pollutants in environmental media whether air, water or soil is modeled by advection-diffusion-reaction equation for concentration (C) with diffusion coefficient (D), velocity (V) and reaction (R):

$$\frac{\partial C}{\partial t} + \nabla.(vC) = \nabla.(D\nabla C) + R \quad \text{.....} \quad (8)$$

This equation is similar to heat advection-conduction equation and has been used extensively in air and water quality studies.

Surface processes

The diffusion equation is also useful to understand hillslope processes, an advection equation is used to understand river long profile and an

advection-diffusion equation helps to deal with landscape evolution. These equations for topography (z) with rate of uplift (U) respectively are as:

$$\frac{\partial z}{\partial t} = k_{hs}\frac{\partial^2 z}{\partial x^2} \quad \text{.....} \quad (9)$$

$$\frac{\partial z}{\partial t} = U(t,x) - KA^m\left[\frac{\partial z}{\partial x}\right]^n \quad \text{.....} \quad (10)$$

$$\frac{\partial z}{\partial t} = U(t,x) + k_{hs}\frac{\partial^2 z}{\partial x^2} - KA^m\left[\frac{\partial z}{\partial x}\right]^n \quad \text{.....} \quad (11)$$

Here k_{hs}, K, m & n are constants and A represents the drainage area. These have been used for a few studies of topographic features on Indian continental regions, such as in Kachchh and the Himalayan region. These equations have now been coded into versatile softwares which are finding increasing application in Earth surface processes globally. Hopefully, such studies on the Indian region will increase.

Systems equations for general Earth system

Major components of the Earth system are lithosphere, hydrosphere, atmosphere and biosphere (including sociosphere and technosphere). In Earth system science, nonlinearity and feedbacks play great role and deduction of emergent phenomena of climate or biogenesis or extreme environmental and social events requires understanding of coupled systems of physical, chemical and biological aspects and their feedbacks. These models are used with the help of a set of nonlinear ordinary differential equations and are applied to investigate the energy and mass transfer and consequent transformations in Earth system. A simple equation where growth or decay of any Earth system variable is seen is in the famous Malthus equation

$$\frac{dy}{dt} = ay \quad \text{.....} \quad (12)$$

Here constant a is positive for growth and negative for decay. This equation is used in population and radioactive dating problems in Earth science.

A modification of this equation helps to understand evolution of any Earth system variable in the presence of limited resources for growth, so called Logistic equation or Verhulst equation, extensively used in large areas of Earth science:

$$\frac{dy}{dt} = ay\left(1 - \frac{y}{K}\right) \quad \text{.....} \quad (13)$$

Here parameter a is intrinsic rate of growth and K the saturation value of variables in the presence of limited resources. In environmental field it is referred as the carrying capacity of region for development and is used extensively in environmental planning.

Two such coupled equations yield oscillatory behaviour in a coupled Earth system variable such as predator and prey in a population:

$$\frac{dy}{dt} = ay - bxy \quad \text{.....} \quad (14a)$$

$$\frac{dy}{dt} = -cy + dxy \quad \text{.....} \quad (14b)$$

Here a, b, c & d are constants. This set of equations is called Lotka-Volterra or predator-prey equations and these find extensive applications in the understanding of biogeochemical cycles.

A further generalization gives Lorenz equation for three variables (x, y, z):

$$\frac{dx}{dt} = a(y - x) \quad \text{.....} \quad (15)$$

$$\frac{dy}{dt} = x(b - z) - y \quad \text{.....} \quad (16)$$

$$\frac{dz}{dt} = xy - cz \quad \text{.....} \quad (17)$$

Here a, b & c are constants. This set of equations are used in climate science to model erratic behaviour so often seen in climate change. However, these set of equations led to studies of chaos in wide areas of science of engineering. It is interesting to observe that the following discrete version of logistic equation too gives a chaotic behaviour:

$$y(n+1) = r(1-y(n)); \; n = 0,,1,2 \ldots N. \quad \text{.....} \quad (18)$$

It is amazing that so much of Earth system knowledge can be constructed by use of these, innocuous, simple looking equations aided by ease of access to computing capabilities.

Algebraic approach

Now as computations have become available easily, all of the above mentioned equations can be reduced to simple problem of linear algebra.

In simplest case we have

$$Ax = d \quad \ldots\ldots\ldots \quad (19)$$

Here unknowns x, and data, d, are connected through a matrix A. Depending upon what we know, solutions are obtained by direct or inverse or machine learning methods. If A and x are given, then the solution using matrix multiplication give the solution. If A and d are given, then solution is obtained by generalised inverse of matrix. When some values of x and corresponding values d are given, machine learning methods give the solution finding A and which then can be used to get d for any x. Numerous applications of first two have been carried out to understand Earth structure and processes, whereas third approach is not so prevalent at present. All or any one of A, x and d would have errors with known or unknown probabilities. This necessitates use of probabilistic reasoning.

A new frontier here is Bayesian approach which aims to improve our prior beliefs based on earlier knowledge to get updated by newer knowledge. It is used to find as to how the prior uncertainty in the knowledge of a random Earth's variable is reduced when new data is obtained. Prior and posterior probability distributions with acquisition of new data are related by Bayes rule:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad \ldots\ldots\ldots \quad (20)$$

Here $P(A)$, $P(B)$, $P(B\backslash A)$ and $P(A|B)$ are probability of A, probability of B, conditional probability of B given A and conditional probability of A given B. Increasingly reliable knowledge of structure and process have been obtained by using such an approach.

Information as a notion for integrated Earth science

Weaver [2] categorised whole science endeavour into simplicity (two bodies interactions), disorganised complexity (infinite number of non-interacting bodies) and organised complexity (large number of bodies interacting nonlinearly and at multiple scales). Earth science problems now look increasingly like organised complexity. Such problems can now be handled only by computing. As whole knowledge is becoming digital, equations of several information measures can be effectively used in developing integrated Earth science. The most famous is the Shannon's information measure, called Shannon entropy, of a random variable, X:

$$S(X) = \sum_{i=1}^{N} p_i \log\left(\frac{1}{p_i}\right); \quad 0 \le p_i \le 1; \sum_{i=1}^{N} p_i = 1 \quad \ldots\ldots\ldots \quad (21)$$

Here p_i refers to probability distribution of *i'th* sample. For continuous random variable, this is modified as

$$S(X) = -\int_{-\infty}^{\infty} p(x) \log p(x)\, dx \qquad \ldots\ldots\ldots\ldots \qquad (22)$$

For many random variables, joint and condition entropies have been defined.

Shannon information theory has been formulated later on as a 'logic of inference'. Understanding of Earth system as organised complexity can be enhanced by using information theory as the logic of inference. Desired probability of a random Earth's variable is obtained by maximizing entropy of the variable given constraints on it (algebraic equations/ inequality or ordinary or partial differential equations or their combinations) using Lagrangian multiplier theory. This framework for Earth science inference requires high computing resources, which are now available.

Next, the future

There have been three paradigms for model building: Newtonian, qualitative and algorithmic paradigms [3]. In the above, only endeavours using the Newtonian paradigm of differential equations have been indicated. Now we have an artificial intelligence (AI)/machine learning (ML) era which uses algorithms.

AI/ML is the current version of erstwhile pattern recognition of sixties. Bishop [4] in his highly cited book, Pattern Recognition and Machine Learning states: "Pattern recognition has its origins in engineering, whereas machine learning grew out of computer science. However, these activities can be viewed as two facets of the same field." All the tools used are same/similar. What has changed is the phenomenal rise of computing capabilities and its availability to almost all, to varying extents. In super computing, machines have already reached 10^{20} (16-bit FLOP/s) in 2025 in classical computing. More advanced capabilities are anticipated through the use of quantum computing, a focus of current researches.

There are attempts to design knowledge creation by keeping AI as the base of everything else. ML is largely data–driven focussing on classification, clustering, regression and model reduction. The large language models (LLMs) like ChatGPT have taken over in constructing knowledge. A frequent question arises, is it "The End of Theory" [5], so is it the end of equation-based thinking? However, equations are "for eternity" as per the quote from A. Einstein mentioned in Introduction.

So, what about future of equation solving in this AI/ML era? It is seen that solutions of mathematical equations are obtained in terms

of mathematical functions. Neural networks (NN) are great tools to approximate any mathematical function. Following equation shows neural network approximation of a function *y(x)*:

$$\hat{y}(x) = c^T A\sigma(Wx + b) + c_0 \quad \text{.....} \quad (23)$$

Here σ is activation function, c_0 is bias and *c, A, W,* & *b* are parameteres of network. Neural network are finding applications in solving complex set of equations used in climate studies. Rather than using full simulation of governing equations, we can now use simpler emulation models. Here model equations are used for a variety of different situations, for instance the nature of Earth's surface and generate input and output pairs on which NN methods are trained to get emulations. This then can be used for further development and decision making in Earth system governance, a topic which gains greater focus in future.

The question of how will AI/ML impact future of researches in Earth science? It is a matter of great challenge and equally great opportunity. Patterns in natural world are represented in terms of mathematical objects. History shows that this process is continuously progressing. History also shows that with time mathematical objects (such as tensors, infinity) developed without any application in mind and as purely mental abstractions, now find applications in understanding reality. In due course these objects too will become part of mathematical AI, which may reduce biases/ hallucinations/ unreality in AI results.

Another trend is about use of agentic experts in the generation of new hypotheses, keeping in few or all kinds of data and expert knowledge. We would have GeoAgents (AI Earth Scientist) experts in policy, data science, geology, geophysics, geochemistry, meteorology, oceanography, remote sensing, accumulators of knowledge, critics and many more. These hopefully can generate hypotheses which help in knowledge creation. And, these agentic experts while interacting with each other and also with those from outside GeoAgents category, generate emergent hypotheses.

Another trend is to build foundation model [6] for the total Earth system using machine learning methodology which then can be used by workers of different sub-disciplines of Earth system. Such endeavours are underway in many disciplines. For instance, a foundation model, using different geophysical data, called Aurora (with 1.3 billion parameters) has been designed to answer a wide variety of questions about air quality, oceanic and climatic events [6]. It would now require building an ecosystem for team research, which is urgently needed in the country. We have a good experience of studying ocean circulation and monsoon system and the time is now ripe to extended this expertise to understand the entire Earth system.

Earth has been investigated by using known fundamental natural laws such as those related to classical mechanics, thermodynamics, electromagnetism, quantum mechanics and relativity. It would be of interest to explore the implications of the currently pursued quantum entanglement (QE) with the hope for providing new ways for computing in Earth science? This has also been likened to another resource like energy from which useful work can be derived. Can application of tools based on QE be used to fathom Earth's far and deepest mysteries?

Regarding how the scope will be of Earth science in future? I believe there would be concerted effort to extend Earth system science to include other planets and further include star (sun) formation studies. So Earth's behaviour will be looked from cosmic perspectives, as ancient sages looked centuries back. This is possible to do as requisite computational tools are now available. A quantitative story of Earth's structure and evolution since the start of its accretion in solar nebula would be realized. How energy, mass and information exchanges and transformations have been taking place inside the Earth and amongst all planets and sun will be a grand story that also includes the understanding of co-evolution of inanimate and animate elements of the Earth, including taking into account the natural selections of chemical elements and species. So far human species have dominated over other species. Further it would be also possible to know what is stored in future of this co-evolution, and especially likely destiny of humanity's habitability, a species who selfishly tries to control this grand story of co-evolution.

In today's data-driven world, use of mathematical equations that satisfy all previous reliable data, should not be underestimated. A little investment in mathematical equations-based studies can lead to meaningful, large intellectual rewards. To quote Bertrand Russell: "Physics is mathematical, not because we know so much about the physical world, but because we know so little. It is only the mathematical properties that we can discover." This interesting statement is eminently true for Earth sciences, as well.

Concluding remarks

There was a time when natural laws could be developed directly to understand the Earth system. Thus, Earth could act as laboratory for novel natural laws. For instance, Albert Einstein had expressed that Earth magnetic field can by understood only from a new fundamental law of rotating bodies. Experiments did not support this novel idea and the origin of Earth's magnetic field was explained using classical natural laws. So far in Earth science, natural laws built by physicists and written using mathematical language have been sufficient for creating knowledge.

It would be highly satisfying if Earth scientists go very deep in their investigations using the mathematical equations and then see the unity of fundamental basic constructs underlying all sciences.

We have described above a few equations which have led to construction of interesting knowledge about Earth. However, the new focus will also include the Earth system governance, which in planning would be called a wicked problem. It would require integrated science using physical, chemical, biological and societal laws/equations to build reliable knowledge. All Earth's structures and processes ultimately can be viewed as information and information transformation resulting into integrated Earth science. Current era, which is being driven by artificial intelligence, would hopefully yield newer ways in which mathematical equations will play their rightful role in creating and using Earth science knowledge equitably and ethically.

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Diet, Nutrition and Health — Challenges and Opportunities

Mahtab S. Bamji

Scope

India faces a double burden of pre-transition diseases (infections and undernutrition) and post-transition diseases (obesity and non-communicable diseases). Intrauterine malnutrition influences both. While the clinical forms of undernutrition have become rare, sub-clinical undernutrition assessed through biochemical tests (some developed in India) persists. More than 50% women and children suffer from anaemia (despite anaemia prophylaxis programme) and more than 50% people suffer from vitamin D deficiency despite ample sunlight. A complex interplay of dietary, physiological, and socio-economic factors contributes to iron dysregulation. Vitamin C promotes iron absorption. PM2.5 mass pollution adversely affects anaemia, causes acute respiratory infection, and results in low birth weight. Respiratory infections and hormonal contraceptives impair vitamin status. Former by affecting vitamin metabolism and increasing urinary losses, and latter by increasing requirement of vitamins by inducing vitamin binding proteins — apoenzymes of B-vitamins, carrier protein of vitamin A. Biochemical bases of the aetiopathogenesis of Protein calorie malnutrition and oral lesions of B vitamin deficiency have been elucidated.

The nutritive values of Indian foods, nutrient requirements of Indians and dietary guidelines for Indians have been systematically investigated using state-of-the-art methodology with revisions over the years. These have helped formulate the National nutrition programmes. Indian diets are qualitatively deficient in micronutrients (hidden hunger). Homestead production of vegetables, fruits and eggs with nutrition education has positive impact on rural household's diet and women's understanding of health and nutrition.

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Introduction

Health is one of the most important determinants of development. The determinants of health are: nutrition, environment, genetics and microbes residing in the body, particularly the gut microbes — Microbiome. All of these are interdependent.

Bill Gates has said, ***"If he can wave a magic wand to solve any global health problem, he would use it to end malnutrition"***. It's easy to understand why. Almost every challenge we face in global health and development is made worse by malnutrition. It makes sick children sicker and poor countries poorer. It robs young people of the opportunity to reach their full potential. And it traps communities in cycles of poverty [1].

Today, most developing countries like India face the double burden of disease. While the pre-transition undernutrition and communicable diseases, persist, post-transition ailments — obesity, diabetes, hypertension, cardiovascular diseases, are increasing. India is the diabetes capital of the world. Undernutrition during pregnancy influences both. The above factors also influence cancer.

Food security Vs Nutrition security

Nutrition security goes beyond Food security, and is defined as "Physical, economic and social access to an age-appropriate balanced diet, safe drinking water, environmental hygiene, and primary health care for all". Awareness regarding these in the community plays an important role.

National nutrition surveys

Comparison of National Family Health Surveys – NFHS5 (2019-21) [2] and NFHS4 (2015-16) (Table 1) shows that over 17 % children are born with low birth weight with little improvement between the two surveys 5 years apart. Under-nutrition as judged by anthropometric indices and anaemia persist particularly in women and children. More recent Poshan tracker data of June 2025 show persistence of stunting at 37% [3]. Concurrently a marked increase in the prevalence of non-communicable diseases is seen.

Country-wide diet surveys by the National Nutrition Monitoring Bureau, (NNMB-NIN 1991, 2002, 2006) [4] show that the cereal-based Indian diets are qualitatively deficient in micronutrients (vitamins and minerals) leading to hidden hunger. If energy requirement is met, protein requirement may be met, but the quality of protein is a problem. In a family, diets of women and children tend to be more deprived.

Table 1: *Comparison of NFHS 4 Vs 5 data*

Parameter	NFHS 5, 2019-21	NFHS 4 2015-16
Prevalence of low birthweight	17.4	17.6
Neonatal mortality rate	16.8	20.0
Infant mortality rate	26.4	27.7
Under 5 yrs mortality rate	29.4	31.7
Breast feeding within 1 hour after birth	68.2	67.0
6-23 months old receiving adequate diet	9.2	10.1
<5 yrs children stunted – Ht/age %age	36	38
<5 Yrs children under weight (Wt /age) %	30	36
<5 Yrs children wasted Wt/Ht % age	19	21
Women BMI < 18.5 I (Wt/Ht^2) %	18.9	22.8
Men BMI < 18.5 I (Wt/Ht^2) %	16.2	21.5
Women BMI > 25 I (Wt/Ht^2) %	31.1	28.6
Men BMI > 25 (Wt/Ht^2) %	32.3	24.2
Children 6-59 months old Hb <11 g	70	67
Non-pregnant women Hb < 12 g	57.8	56.9
Pregnant women Hb < 11 g	53.2	48.2
Men 15 -49 yrs old	25.1	19.2

While the above-cited surveys have provided valuable information on health and nutrition scenario in India, only the NNMB surveys included diet survey. But these also were confined to 10 states and did not include blood markers. A Comprehensive National Nutrition Survey [5] estimated the nutritional status, blood biomarkers and dietary intakes in all states and UTs. However, it covered only 1 to 19 years age group and lacked a comprehensive nutrition assessment [6, 7]. A comprehensive nutrition survey has just been completed by NIN. It includes dietary and nutrient intake data along with anthropometry and blood biomarkers and will facilitate evidence-based public health nutrition policy formulations. It is the first of its kind in the world with huge data that can also feed AI for data interpretation and future use (R Hemalatha, Personal communication).

Despite being among the top three producers of vegetables and milk; intake of these foods is low due to lack of awareness and affordability besides insufficient production. Green revolution has increased the production of cereals, but legumes and millets have been neglected. Green revolution was resource intensive and has had adverse impact on the environment. Food wastage, faulty cooking habits and false beliefs

about foods like papaya and banana should be avoided during pregnancy add to the problem. Global warming has additionally compromised crop productivity.

The problem of gender gap

In the World economic forum's Global Gender Gap Index (2025), India's rank is 131 out of 148 countries. Some improvement in education is seen, but the gender disparity remains in areas of economic participation, decision making, and health and nutrition. This is also apparent from the periodic analysis of India's progress in UN's, 17 Sustainable Development Goals (SDG) by the NITI Aayog (2023-24) [8] (Table 2). While all SDGs impact nutrition, the table lists the first 6 goals which have maximum impact. This analysis also shows lowest improvement in Goal 5 gender equity, followed by the Goal 2, zero hunger (which includes agriculture and nutrition). Best progress is seen in the Goals 7 (clean energy) and Goal 6, (Clean water and sanitation — perhaps due to the impetus given to the *Swacch Bharat* programme) followed by goal 1 on No poverty, perhaps due to emphasis on economic development.

Table 2: *India's Progress in the Sustainable Development Goals (SDG). % of target achieved*

	SDG 1 No Poverty	SDG 2 Zero hunger	SDG 3 Good health	SDG 4 Quality education	SD 5 Gender equality	SD 6 Clean water sanitation
2023-24	72	52	77	61	49	89
2020-21	60	47	74	57	48	83
2019-20	50	35	61	56	42	88
2018	54	48	52	52	36	63

Causes and consequences of Low Birth Weight (LBW)

The problem of malnutrition begins with intrauterine growth retardation and low birth weight (<2.5 Kg). Maternal malnutrition, maternal age, premature birth, lack of antenatal care, infections and inadequate rest are the major causes of a child being born with LBW. The consequences of LBW are: high morbidity and mortality, slower growth rate — stunting, impaired physical and mental performance, adverse future pregnancy outcome of the daughters and foetal origins of adult diseases (Barker hypothesis). According to WHO, the first 1000 days after conception are most critical for foetal and child health and rehabilitation.

Care during the first thousand days after conception – WHO

The general guidelines are:

1. Eat more food during pregnancy,
2. Avoid food taboos during pregnancy,
3. Initiate breast feeding within 1 hour after birth,
4. Exclusive breast feeding for 6 months,
5. Complementary feeding from 7th month,
6. Continue breast feeding beyond one year along with complementary feeding.

NFHS surveys (Table 1) show that while more than 60% mothers initiate breast feeding within 1 hour after birth, less than 10% initiate complementary feeding after 6 months. The former is probably due to marked increase in institutional deliveries. In the villages of Medak district of Telangana where the author works, home deliveries by *Dais* has become a history and almost all women initiate breast feeding within 1 hour. Initiation of complementary feeding has also increased substantially through behavioural change communication (BCC) [9, 10].

Foetal origins of adult diseases: Barker hypothesis

Those born with low birth weight due to intrauterine malnutrition (IUGR) are more susceptible to lifestyle associated diseases like type II diabetes, hyper-lipidaemia, hypertension and CVD in later life. Their bodies have higher fat content — lean fat babies. Indians tend to have higher percentage of body fat than muscle.

The message is clear. There should be a life-cycle approach in caring for health and wellbeing of females from birth.

India's journey in nutrition research

Though nutrition research is conducted in some departments of medical colleges and home science colleges, the National Institute of Nutrition (NIN) is the only institute of its kind in India and perhaps in the world, completely dedicated to nutrition research. NIN's journey in nutrition research over 100 years has been reviewed [11]. NIN's uniqueness lies in having access to patients suffering from malnutrition through dedicated wards in two government hospitals in Hyderabad. A dedicated field unit conducts community-based research. Well-equipped pathology and biochemistry divisions, an extension training division, a statistics division and a modern animal facility with big and small laboratory animals facilitate linking research in nutritional biochemistry and molecular biology with deficiency diseases. A food and drug toxicology division was also created. Such a variety of facilities has enabled the author to elucidate the biochemical bases of some of the clinical and community-based observations.

Nutritive value of indian foods

A major contribution of NIN since 1935 has been analysis of Indian foods for their nutritive value, in respect of energy, carbohydrates, proteins, fats, vitamins and minerals. Use of state-of-the-art and evolving methodologies leads to periodic revision. The relatively recent versions are [12, 13]. These values are averages with the scope of individual differences. A recent study [14] on mangoes shows considerable variation in both content (total carotenoids) and composition (individual carotenes and xanthophylls) among the cultivars.

Dietary requirement of nutrients for Indians

Nutrient requirements of populations and individuals can vary. Over the years NIN has discussed this using the available evidence and has made two types of recommendations comprising Recommended Dietary Allowance (RDA) and Estimated Average Requirement (EAR). While EAR is the median of the intake of a healthy population, RDA is its upper limit, the 97.5 percentile. Former is generally used while recommending dietary intake for general populations, latter helps deal with deficient individuals (ICMR-NIN expert group 2020 [7]. A manual for Dietary guidelines for Indians-2024 [15] facilitates translation of Nutri centric RDA of nutrients into food-based approaches for populations. It is an important tool for promoting healthy eating habits and preventing diet-related chronic diseases in India. Supplementary food planning for national programmes has been facilitated by this information.

The primary evidence for indispensable amino acid requirements of humans, as recommended by the 2007 WHO/FAO/UNU Expert Committee, was generated at the St John's Medical College in Bengaluru, using a unique Indicator Amino Acid Balance Method [16, 17]. Subsequently, a novel and unique dual-isotope method was developed to evaluate the digestibility of plant and animal proteins to meet these amino acid requirements, particularly in vulnerable populations living in challenging environments where protein digestibility may be affected. Use of this method showed that the amino acid digestibility of extruded chickpea and yellow pea protein was high and comparable in moderately stunted South Indian children [18-22].

Functional foods and nutraceuticals

Besides the known nutrients, many plant foods contain bioactive substances that promote health, and reduce disease. The term functional foods and nutraceuticals are used interchangeably and one of the preferred interpretation is: nutraceuticals are the bioactive compounds in functional foods, which are given in concentrated medicinal form [23]. Such health

promoting properties are found in a variety of carotenoids, flavonoids, phenolic compounds, protein hydrolysates, oils fatty acids, dietary fibre and spices—commonly used in Indian cooking [24, 25]. Turmeric, has been investigated for anti-inflammatory, antioxidant and anti-carcinogenic properties [26].

Nutrition microbiome and gut health–prebiotics, probiotics and postbiotics

The good microbes (Lactobacillus, Bifidobacterium, Saccharomyces) residing in the body, particularly gut, are called probiotics when given as supplements or as nutraceuticals. There are over 400 microbe species in the normal gut out of which Bifidobacteria is dominant during infancy and childhood.

Foods like non-digestible fibres (inulin and fructo-oligosaccharides) that promote probiotics are called pre-biotics and their metabolic byproducts produced by fermentation are called post-biotics [25, 27]. It is claimed that probiotics have beneficial effects on immunity, many degenerative diseases, cancer and neurodegenerative diseases.

Recent studies in India have found that the gut microbiome plays a major role through the gut-brain axis in prevention and management of diseases like Parkinson's, Alzheimer's, Cognitive impairment and Senile Dementia [28-30]. Gut dysbiosis significantly contributes to neurodegeneration due to enhanced inflammation, a leaky gut and decreased production of short chain fatty acids. Key neurotransmitter systems, particularly glutamate, GABA (gamma-aminobutyric acid), and serotonin pathways mediated through the gut microbes seems to be a major causative factor. Reversing this process through appropriate dietary, pre-, pro- and post-biotics interventions are being evaluated and may help in management of these conditions (B. Sesikaran, personal communication).

For every clinically manifested disease, there are many who suffer from subclinical deficiency which can be detected through biochemical and molecular tests.

Till the end of the last century, clinical forms of nutrition deficiency diseases like kwashiorkor and marasmus (protein calorie deficiency), beriberi (thiamine deficiency), pellagra (niacin deficiency), lesions of the mouth like angular stomatitis and glossitis (deficiency of vitamin B, particularly riboflavin), scurvy (deficiency of vitamin C), rickets (deficiency of vitamin D and calcium) were common in India. Today, they are not. But subclinical manifestations (anthropometry, biochemical, molecular changes) with adverse health consequences do persist.

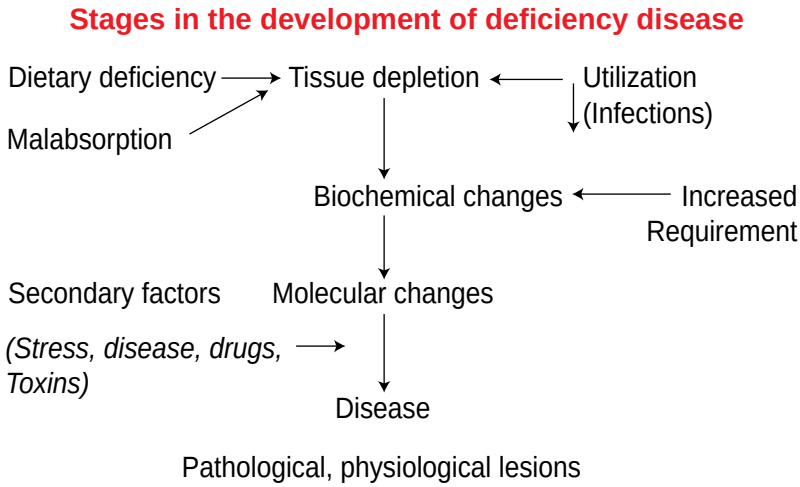

Figure 1: *Stages in the development of nutritional deficiency*

Biochemical assessment of micronutrient status

The status of nutrition can be assessed through clinical, anthropometric and biochemical methods. Biochemical assessment of micronutrients can be done through examination of blood (serum, RBC) and urine levels. For some B-vitamins, enzyme-stimulation with coenzymes-tests are available. e.g. Transketolase test, (vitamin B1), glutathione reductase test (vitamin B2), Aspartate amino transferase test (vitamin B6) [31]. The glutathione reductase test for vitamin B2 was developed by the author [32]. Using these tests, high incidence of B-vitamins — deficiencies in mothers and new-borns were observed [33].

Recent research of Bhanuprakash Reddy and colleagues shows persistence of a high prevalence of biochemical micronutrient deficiencies in children, adolescents and adults [34-38]. In adults, dietary deficiency was also observed. Their studies also showed that individuals 60 years have significantly shorter telomeres and lower mitochondrial DNA copy number — indicators of biological aging. Both these indicators were positively associated with plasma folate (B9) and B12 levels [39].

Effects of respiratory infections on vitamin nutrition status

Studies in rural school boys and pre-school children showed higher incidence of vitamin B-responsive, oral lesions during respiratory infections. This was associated with increased urinary loss of vitamin B, leading to its deficiency [40, 41]. Animal studies elucidated the cause to be impaired utilisation due to reduced conversion of riboflavin (vitamin B2) to FMN [42].

Effects of oral contraceptives on vitamin nutrition status and diabetes

High incidence of biochemical vitamins deficiency has been observed in women using oral contraceptives [43]. Steroid contraceptives affect vitamin metabolism by inducing certain apo-enzymes (vitamins B) or transport proteins (Vitamin A). This increases the demand of vitamins leading to their relative deficiency [44, 45]. The diabetogenic effect of contraceptive steroids users is due to impaired glycolysis. It can be reversed with excess vitamin B6 (pyridoxin) [46, 47].

Carnitine deficiency in children suffering from PCM

Carnitine plays a role in the metabolism of fatty acids. In the body the essential amino acids lysine and methionine are needed for its synthesis. Studies in children suffering from clinical and non-clinical PCM showed marked reduction in plasma carnitine and albumin levels, perhaps due to PCM associated deficiency of the above essential amino acids [48]. Studies in humans showed that trimethyllysine is an intermediate in the conversion of methionine to carnitine [49].

Spirulina as a source of vitamin A

Vitamin A deficiency is an important problem in India**. S**tudies in rats and humans showed that the blue-green algae Spirulina is a very good source of vitamin A, besides protein [50].

Etiopathology of nutrition deficiency diseases

Protein calorie malnutrition

The two pathological manifestations of protein calorie malnutrition are — kwashiorkor and marasmus. At one time it was believed that marasmus which manifests as a severely growth retarded, emaciated child is due to food deficiency, and kwashiorkor which manifests itself as oedema in a child is due to protein deficiency. Research of Gopalan and Jaya Rao showed that both the manifestations are due to protein-calorie malnutrition. While in a marasmic child the metabolic process (response of the adrenal cortex) is well-preserved due to good adaptation to stress; failure of this adaptation tips the balance to a more severe disease, kwashiorkor [51].

Metabolic obesity in malnourished children

In a paradoxical observation Sachdev et al. [52] have reported double-burden of anthropometric undernutrition and "metabolic obesity" in Indian children. This phenomenon needs further research on remedial measures.

Anaemia

Anaemia remains one of India's most pressing public health problems (Table 1), with causes extending beyond iron, folic acid, vitamin B12 deficiencies. A complex interplay of dietary, physiological, and socio-economic factors contributes to iron dysregulation [53, 54]. Iron uptake is impacted by low gastric acid production, vitamin A deficiency, chronic inflammation, and food matrix interactions [55]. Human enterocyte cell line models (Caco-2) have been developed to assess iron bioavailability from foods and biofortified crops [56]. Vitamin C, facilitates iron absorption. Inclusion of a vitamin C-rich fruits like guava in the meal of ICDS (Integrated child development services) children has a positive impact on haemoglobin levels besides reducing respiratory infection [57, 58].

Chaudhary et al. (2023) [59] reported the adverse effects of pollution with $PM_{2.5}$ on prevalence of anaemia, besides acute respiratory infections and low birth weight.

Vitamin D deficiency

Since vitamin D3 (cholecalciferol) is synthesised in the skin from 7-dehydrocholesterol on exposure to ultraviolet light and released into the bloodstream, in bound form (along with Vitamin D-binding protein) the possibility of vitamin D deficiency in a tropical country like India, where there is abundant sunshine throughout the year, was not expected. However, relatively recent studies show that vitamin D deficiency is a public health problem – prevalence of > 50% as judged by serum 25 (OH) D3 levels <20 mg/ml [60]. Vitamin D is converted to 25 OH vitamin D in the liver and then to its active form, 1,25 Dihydroxy vitamin D in the kidney. The main function of vitamin D is to facilitate calcium absorption and bone mineralisation. Its deficiency leads to rickets in children and osteoporosis and osteomalacia in adults. While rickets has become relatively rare the other two conditions are common. Recent studies show extra skeletal benefits of vitamin D in infectious, autoimmune and non-communicable diseases [61].

The high incidence of vitamin D deficiency in a country like India is attributed to the style of clothing, and inadequate exposure to mid-day sun. Dietary calcium deficiency in India is also a major problem.

Biochemical–molecular basis of the skin lesions of vitamins B2 and B6 deficiency

Lesions of the mouth such as angular stomatitis and glossitis are generally attributed to vitamin B2 (riboflavin) deficiency whose prevalence

is high in India. Drs Leela Raman, and Kamala Krishnaswamy from the clinical division of NIN, observed that in patients, these lesions often fail to heal by treatment with vitamin B2, only. For total healing vitamin B6 (pyridoxin), is also needed (personal communication), suggesting a common biochemical basis involving both these vitamins. This prompted the author to investigate the relationship. After some preliminary investigations it was hypothesised that the Biochemical–Molecular basis of the skin lesions of the mouth, which respond to vitamins B2 and B6 is-impaired skin collagen cross linking due to raised levels of Homocysteine in blood. Defective collagen cross linking affects the overlying epithelial tissue of the skin leading to the pathology. Homocysteine impairs collagen cross linking. Both riboflavin and pyridoxine are needed for the metabolism of homocysteine (Fig. 2) [62].

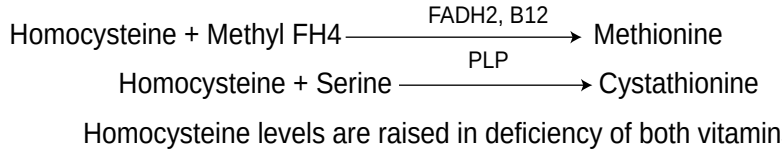

Figure 2: *Role of vitamins B2 and B6 in homocysteine metabolism*

FADH2 is the active co-enzyme form of vitamin B2 and PLP (Pyridoxal phosphate) is the active form of vitamin B6. Studies in rats showed that as hypothesised, in the deficiency of both the vitamins, homocysteine levels are raised and collagen crosslinking is impaired [63, 64]. Raised levels of homocysteine is also a risk factor for cardiovascular diseases. Considering the high incidence of vitamin B2 deficiency in India, its role in the prevalence of CVD needs to be researched.

Some of the earlier studies on pathogenesis of Pellagra, burning feet syndrome, genuvalgam, fluorosis etc have been reviewed [6]. Studies of Krishnaswamy and colleagues on diet nutrition and cancer have also been reviewed [65].

Approaches to combating micronutrient deficiencies–the hidden hunger

For health and nutrition security there has to be awareness and access at affordable cost to food security (including correct feeding practices), safe environment and drinking water, correct lifestyle and access to health care.

Approaches to combat micronutrient deficiencies include: a) pharmaceutical supplementation (Anaemia, Vitamin A deficiency),

and b) food fortification (salt, wheat flour, milk, oil) or addition of micronutrient powder to cooked food. Iodised salt is a success story. Iron fortified, iodised salt (double fortified salt) developed by NIN needs promotion. These have been reviewed. While implementing the fortification approach care is needed to ensure that one stays within the Tolerable Upper Limit (TUL) for the nutrient.

The third approach is the food-based approach, comprising dietary diversification through nutritionally sensitive and environmentally sustainable agriculture. Bio-fortification utilising conventional breeding, genetic engineering, and gene editing can help to develop micronutrient-rich plant foods, by enriching the germplasm. ICAR has developed biofortified crops such as iron-rich pearl millet, zinc-rich wheat and rice, and beta-carotene-rich maize and sweet potatoes. Unlike supplementation or fortification, which can address the deficiency of only select nutrients, dietary diversification is a more holistic approach with minimal danger of toxicity. The bias against genetic engineering among some people is misplaced. With appropriate safety measures it provides a powerful tool to combat malnutrition.

Nutrition sensitive agriculture

Crop diversification has become a *mantra* to save water and promote food security. Vegetables and fruits are rich source of micronutrients. The M.S. Swaminathan Research Foundation (MSSRF), at Chennai [66] and the Dangoria Charitable Trust (DCT), Hyderabad [9, 10] have experimented with home gardens to promote household access to micronutrient-rich foods for small and marginal farmers. MSSRF programme was located in select districts of rural Tamil Nadu and Odisha. DCT programme was located in select localities of the Medak district of Telangana. In Telangana the families were encouraged to raise gardens in their farms (homestead gardens) due to lack of space near homes. DCT also introduced backyard poultry with high egg yielding birds.

Technological intervention (home gardens, backyard poultry with high egg-yielding birds) was combined with education on health (DCT) and nutrition. Family diet survey was also done by DCT to assess the impact on the consumption of vegetables and eggs. Free seeds and saplings were given. In Telangana saplings were raised by women in their backyards and sold for the project. For backyard poultry, DCT purchased 4 months old birds from a poultry farm in Hyderabad and sold them to the families. MSSRF assessed the impact through structured interviews, key informant interviews and focus group discussions. Initial and endline Knowledge Attitude and Practice (KAP) surveys were also done by DCT to assess the impact on mothers' knowledge, acceptance

of nutrition gardens and poultry, and impact on diet. DCT specifically targeted families with pregnant mothers and children under 2 years of age — the first 1000 days.

While the overall impact on knowledge of the target families was good, improvements in dietary diversity and overall nutrition were less common in the MSSRF study. In Telangana remarkable improvement in mothers' understanding of health and nutrition was seen. Diet surveys also showed a good impact on the consumption of vegetables and eggs.

Dietary diversification facilitated by agricultural diversification can promote food security. For nutrition security, clean environment, drinking water and health care outreach, along with education, have to be ensured. Nutrition literacy is needed at all levels of governance and in all professions.

Suggestions to Combat Malnutrition through Increased Awareness in the Society

1. Nutrition literacy at all levels—politicians, administrators, teachers, academics, professionals, particularly health and agriculture and community at large, particularly women;
2. Involve media. National heroes—film stars, sports persons, etc can play a big role in creating awareness;
3. Science academies can play a major role in promoting nutrition literacy;
4. Include nutrition as a subject in the syllabus of medical and agriculture courses;
5. Educate school children about healthy diet and avoidance of high fat, high sugar processed foods;
6. Promote dietary diversification, facilitated by crop diversification to improve access to vegetables, fruits and animal products at affordable cost;
7. Include millets and pulses besides cereals, in Public Distribution System through fare price shops;
8. Fight false beliefs like pregnant women should avoid papaya and banana, and eat less food;
9. Fight faulty cooking practices like discarding excess water after cooking and washing vegetables after cutting;
10. Focus on girl child, through adolescence and adulthood. Special focus on the first 1000 days (conception till 24 months). Promote WHO guidelines, for infant and child feeding;

11. Promote gender equality. India lags in the UN's SDG 5, — gender equity;
12. Ensure clean environment, access to safe drinking water, and primary health care.

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Responsible Science, Social Purpose and Community Connect: Meeting the Unmet Needs Through Grassroots and Frugal Innovations

Anil K. Gupta and Anamika Dey

Scope

This paper addresses the gap between national Science, Technology, and Innovation (STI) aspirations (e.g., achieving a five trillion economy) and actual budget allocation (hovering around 0.7% of GDP), emphasizing the need for efficient, innovative, and responsible utilization of existing resources to address unmet and often unfelt needs of disadvantaged people, regions, and sectors. It critiques the historical asymmetries in scientific inquiries where local knowledge providers remain anonymous, and benefits are not shared back with communities.

To overcome these challenges, the paper champions the philosophy of Honey Bee Network (HBN), a social movement initiated about four decades ago to give voice, visibility, and velocity to grassroot ideas, innovations, and outstanding traditional knowledge. The paper notes that despite significant Corporate Social Responsibility (CSR) funds, negligible amounts reach grassroots innovation for scientific validation and value addition. It highlights the importance of leveraging social and ethical capital to mobilise voluntary support from scientists and Intellectual Property (IP) attorneys, who have helped file over 1200 patents pro bono.

The authors propose a broader responsibility for science, one that includes accountability to future generations, nature, the unorganised sector, and women, recognising that the specific challenges and physiological differences of women in areas like clinical trials are often overlooked. They emphasise that a nation

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which primarily consumes digital knowledge content rather than producing much of it for global good requires significant innovation rooted in self-reliance and socio-economic advancement, driven by a systematic identification and validation of local unmet needs.

The paper is divided into four main parts: *Part One: Understanding and Exploring Unmet and Unfelt Needs,* discusses a taxonomy of framing unmet and unfelt needs and the kind of solutions required, drawing on experiences from *Shodhyatras* (knowledge learning and sharing walks). *Part Two: Institutional Conditions*, describes the institutional conditions necessary to nurture a more empathetic and inclusive approach to scientific pursuits, moving beyond conventional R&D and innovation models. *Part Three: Obliterating Disciplinary Boundaries*, summarizes arguments for addressing complex social and ecological needs through community-centric innovations. And part four presents specific policy recommendations to steer national STI policy towards making India a self-reliant society through bottom-up creativity and inclusive growth.

Context

How do we manage an ecosystem where aspirations don't match endowments and yet progress has to be made, relentlessly, brick by brick, from the backwaters of the highest temples of science and technology to the ordinary farms and workshops of mechanics. Prime Minister Vajpayee saw a dream of a two per cent share of GDP in the Science and Technology policy in 2003. A dream reiterated in STI policy 2013. After that, we have aspired for a five trillion economy, but the budget for STI has hovered around 0.7 per cent (tempered by 18% GST). In such a context, it becomes even more necessary that existing resources are used more efficiently and innovatively to get amplified returns than has been the case so far. *Creativity under constraints needs more and not less flexibility.* But we will leave that issue to more knowledgeable people. What we will focus on is how science can be made more responsible, responsive to realize unmet and sometimes unfelt needs of disadvantaged people, regions and sectors.

Assessing the responsibility of institutional science and technology?

About four decades ago, it was realised that most scientific inquiries about local knowledge, innovation, and institutions were asymmetrical and extractive in nature. The knowledge providers remained anonymous while knowledge-collectors became the authors of the knowledge. They were not connected with other knowledge providers through local language communications. The scientists rarely shared their pooled and value-

added results with the knowledge providers. The benefits generated from commercial or other applications of this knowledge were not ploughed back to the communities. It is to overcome such asymmetries, the Honey Bee Network (Henceforth, the HBN, 1987-89), started a new social movement. It helped overcome anonymity, it pursued cross-pollination, it ensured sharing of discoveries and new results with other knowledge providers in the local language and, it ensured fair and just benefit sharing. This was initiated much before the Biodiversity Convention came into force in the year 1992 (Biodiversity, 1992).

Dilemma to the development of HBN: When Prof. Gupta returned from a stint abroad in 1985, he asked a question that led to the HBN. He was paid in dollars for building capacity of the host country scientists to pursue research on farmers and tenants' fields. On return, he asked a question: was all the compensation he received accrued because of his own brilliance or did creative communities about whom he wrote also had contributed towards that? He looked at his income tax return where there was no specific line showing a share of his income going back to the people whose knowledge, wisdom and innovations had contributed to that. He tried to persuade himself that since he worked on moulding public policy, created wider awareness and mentored creative people, was that not enough? But he was not convinced. He realized that just as some landlords might exploit in land market, traders in commodity market, lenders in money market, he was an exploiter in knowledge market. This was a very painful realization and needed a radical resolution. Thus, was born the idea of Honey Bee Network. Honey bee did, what we intellectuals often did not do. It collected nectar of the flowers without impoverishing them. In fact flowers attracted them with different colours. They nourished the nature, the ecosystems. They did not keep all the honey with them some was shared with us. Could we emulate that principle?

The HBN now gives *voice, visibility and velocity* to the ideas, innovations and outstanding traditional knowledge, created at the grassroots. The augmentation of 'velocity' is the toughest part as it involves synergizing *innovation, investment and enterprise*—the three pillars of a viable supply chain embodied in the form of GIAN. HBN model was operationalised through institutions like Sristi (Society for Research and Initiatives for Sustainable Technologies and Institutions), GIAN (Gujarat Grassroots Innovation Augmentation Network), and the National Innovation Foundation (NIF).

The Gujarat Grassroots Innovation Augmentation Network (GIAN) was set up in 1997, jointly by Society for Research and Initiatives for Sustainable Technologies and Institutions (SRISTI, 1993), HBN and Indian Institute of Management, Ahmedabad (IIMA) with the support

of the Gujarat Government. GIAN's model was eventually scaled up into the National Innovation Foundation by HBN in the year 2000.

Without the support of private and public institutions, social entrepreneurs and markets, an innovator cannot achieve *velocity* alone. The scientific validation of any concept, in particular by the public institutions of repute, makes a big difference in creating trust among potential users of innovations, *for* and *from* grassroots. Despite a huge mobilization of funds under Corporate Social Responsibility, only a miniscule amount reaches the grassroots innovation ecosystem, in particularly for scientific validation of and value addition to grassroots innovations. Most scientists who worked with the Grassroots Innovators (GRI) and Traditional Knowledge (TK) Holders , did so on a voluntary and honorary basis i.e., without remuneration. So also the attorneys for intellectual property, who helped file over 1200 patents, did not seek any financial remuneration. It shows that social and ethical capital of the HBN can indeed help in mobilizing and saving financial capital.

Extending the responsibility of science

What are the factors that a society expects scientists to take care of while linking science with society. These are:

1. to what extent the concern of *Perfect strangers* has been taken into account. The perfect strangers are unknown and unknowable that is, unborn. We have to determine the impact of research and innovations on future generations so that they don't complain about our lack of responsibility towards their interests;
2. How responsible are the new innovations towards Nature including non-human sentient beings such as the ants, squirrels, birds and so on. It is eminently possible that not all environmental effect can be anticipated at the beginning but, any responsible science detects error quickly and takes remedial action expeditiously. No purpose is served by obfuscating the emerging externalities as unavoidable costs.
3. How well the problems of unorganized sector are included in agenda of scientists as the poor cannot sponsor projects and provide material resources. *Poor are not a project but serving their interest is the purpose.* As discussed later, this calls for a systematic effort to map their unmet needs, so that societal responsibility is consciously mainstreamed.
4. While developing solutions, how well are the problems of women understood given that invariably these are neglected. Amongst glaring lapses is their poor share (< 20-30%) in clinical trials for new drugs

(thereby neglecting women and in them differences in-pre- and post-menopausal conditions) to understand reaction of drugs with their physiological specificities; and,

5. How well are the missing links across disciplines, sectors, professions and agro and socio-ecological systems bridged?

Accountability of scientific pursuits particularly those with immediate implications for nature, climate resilience or communities, needs to be explicitly specified so that inclusive development including the interests of perfect strangers can be planned for.

We discuss first, the taxonomy of framing unmet and unfelt needs and the kind of solutions that could be planned with due cognizance of the consequences of different approaches. Thereafter, part two discusses the institutional conditions which nurture an empathetic approach to scientific pursuits. Part three summarizes the arguments for obliterating disciplinary boundaries when addressing unmet social and ecological needs through innovations from and application to grassroots communities. Finally, part four presents policy recommendations to steer the STI policy to make India a self-reliant and socio-economically developed society. We strongly argue that a country which downloads thousands of times more content than what it uploads, will need many unprecedented breakthroughs to be counted as a leading knowledge society, among the comity of developed nations.

Understanding and exploring unmet and unfelt needs

Every unmet need can be met by multiple solutions, and it could even be a potential market for economic or social goods and services. There is a strong case for talking to creative people at grassroots level, as is attempted in *Shodhyatras (knowledge sharing and learning walks)* carried out by the authors and their group. Some of them have already identified unmet needs and addressed them through local scale grassroots innovation. Every grassroots innovation indicates an unmet need identified and addressed to, by a common person — mostly untrained and often unschooled. These solutions need not be and often not optimal, but are helpful to an extent. There is a need for scientists and technologists to work with these innovators to improve their product for an optimum delivery and document the process of co-creation with due credit to the innovator in identifying an unmet need and addressing it, even if sub-optimally.

There are also needs which are not even felt and thus may not be articulated. An example is the conservation of agro-biodiversity. In the wake of green revolution high yields through monoculture and

chemical inputs made scientists and communities ignore the need to preserve local agro-biodiversity, so critical to conserve genes for climate resilience. Now when climatic fluctuations are taking a toll of the production system and soils have lost their microbial diversity, need for conservation of agro-biodiversity and soil health is being felt and articulated, even if belatedly. These needs can be identified by the navigation through moral and professional compass of a scientist using the human dignity, integrity and sustainability framework. Green revolution removed the shortage of food in many developing countries. It was apparent to the scientists that application of macro nutrients (like N, P, K) and that too in an unbalanced manner in a balanced manner can lead to deficiency of micronutrients. We still lack a portable micro-nutrient measurement device for the farmers. Farmers have not felt the need for such a device because native micronutrient reserve of soil somehow has not become critical for so long, due possibly to lower draw-down and available native soil fertility. But signals of deficiency started appearing in early eighties. The deficiency of micro nutrient in soil will get transferred to human health through food, animal milk or other product chain.

There is a dearth of studies on soil, crop, animal, and human health. The people affected by chronic diseases did not realise the need for data on this chain and thus did not articulate this unmet need. Public Health Scientists neglected the study of this linkage, thus missed creating a constituency for soil health linked to human health. Portable and affordable devices for study of soil microbial health are still to be developed. Many such unfelt needs remain unmet because spectrum of responsibility of scientific pursuits has not enlarged its scope broad and deep enough to cater to the society.

Even if such unmet needs are recognized, not all solutions may occur to a particular domain specialist or may come from within the organisation. The need for inter- or trans-disciplinary science is often articulated, but never acted upon with the sincerity and sensitivity that such issues deserve. Thus, if one seeks to find out the presence of social scientists working in institutions dealing with natural or physical sciences, one would invariably draw a blank, in many countries, including India.

First solution need not be the best always, and a continuing chain of trial, error, failure and redesign, and revalidation of the need, with multiple iteration with desired potential stake holders, is needed. An international organisation working on the problems of dryland crops spent millions of dollars over several decades to realise, what was obvious to the farmers in rainfed regions that experienced drought three years out of five. The

economy of such farmers was often dependent upon livestock, and thus they needed a larger quantity of palatable and nutritious fodder. Not many crop breeders screen the F2 to F4 generation of segregating population of rainfed grain crops while crossing and breeding new varieties for livestock palatability and nutrients. Co-creating solutions with knowledge-rich, economically poor farmers helps. But co-creation also requires respect for the knowledge and wisdom of common, uncelebrated but creative people.

Every need begets another need, and thus solutions must be conceived in a dynamic and iterative context. Every satisfactorily met need, enhances the anticipation of people (and rightly so), meeting of higher order needs. This is a sign of an aspirational society willing to expect more after meeting some of the basic needs. Unlike Maslovian hierarchy, it may be remembered that search for enlightenment is not contingent on basic needs, after all Kabir, Rahim, Sant Ravidas achieved enlightenment despite engaged in struggle of meeting their daily needs.

A caveat here is that one should never try to meet all aspects of an unmet need in the very first solution, or first attempt. This will ensure that a search for complete solution will not delay the less perfect solutions being made available to needy people. Incorrigible improviser is the characteristic trait of many not-so-successful grassroots innovators; they keep improving their initial solution. Sometimes, it is okay to start with an imperfect but functional solution as version one, and then keep improving with successive versions over time.

Users are an important part of co-creation and should have a say but they may not always be aware of best trajectories to meet their needs. There is a scope for a supply-side solution through an intuitive understanding of the community's needs. After all, no Asian farmer ever demanded a dwarf wheat variety, which brought about the food revolution because they had not seen it or thought about it. It was a supply-side intervention that worked well in many respects but their effect on the reduction of agro-biodiversity, soil nutrient mining, heavy dependence on chemical inputs, and in some cases decline of the water table, etc., was discovered only later, though most of it was anticipatable.

A proper definition of an unmet need is half the solution; one ought not to save effort in this pursuit. Sometimes short-cut methods are used to identify needs by spending pennies on this research. Thereafter millions are spent on meeting poorly identified needs. In such cases, failure is *fait accompli*.

There is no substitute for immersive learning. Prof. Tu Youyou headed a program in China to find control for malaria. She wanted to understand

the severity of the problem first-hand. She went to a malaria-prone region and experienced the pain of the families affected by the disease and death. That immersive experience gave her a personal passion and purpose to find a solution. She later discovered artemisinin from a plant disclosed in an ancient manuscript after screening around 2000 plants. Before doing trials on others, she tested its effect on herself and found it safe. The problem arose that the fever was going down and up again. She again looked at the traditional knowledge sources and found an old manuscript which mentioned that people used this plant extract to soak in cold water. She was using boiled water extract. The Cold water extract stabilizes the compound. Thus, artemisinin was discovered for which Prof. Youyou got Nobel Prize in 2015.

Responsible science and immersive learning require that there is no trade off with rigour and recognition. It is also important that the ancient wisdom (wisdom of elders) is not ignored but be blended with modern science to address many unmet needs to create a frugal and accessible solution.

It is useful to clarify the meaning of frugality or More from Less for More [1]. Much of the literature has focused on frugality for consumer and manufacturers only. Frugality for environment is equally important though ignored while conceptualizing such innovations. A one-rupee sachet of any product is an affordable and frugal choice for consumer and manufacturers but is an environmental disaster. If the cost of collecting a piece of plastic from 650,000 villages is calculated then the solution of a one rupee sachet of non degradable plastic becomes a very *costly* innovation, needing billions to remedy its consequences. This makes it an irresponsible innovation and implies that circular economy has to be embedded in every transnational endeavor.

Translational models for frugal innovations

There are different ways in which scientists can translate the laboratory technologies into social applications. Some examples are:

1. One makes a readymade cloth and gives it to the user,-in a take it or leave it, manner. The user has no choice except to use it as it is. It does not have much scope of modification in the hands of the users and some may try to repurpose it.
2. One gives a semi-stitched cloth to the users and they get it finally stitched accordingly to their needs to have final dresses. User has some choice to shape the final form of the solution according to their agro- and socio-ecological and institutional conditions. The gender differences may be incorporated in this adaptation process.

3. One talks to users, understands their needs and then co-designs the weave and stich of the cloth they need. A need driven collaborative design model may advance the fit between the unmet need and the possible co-created solution/s.
4. One studies the way users cope with the problems, identifies the most successful or healthy users who have either not faced the problem or have resolved it through their own knowledge and creativity, and builds upon this knowledge, adds value and improves the effectiveness of local solution/s. To illustrate, Robert Abramovitch, a Michigan State University microbiologist and TB expert, found that a centuries old Chinese traditional medicine derived artemisinin helped in control of TB by not letting Tb bacterium become dormant (Otherwise, patients get a false sense of relief during dormancy, making treatment longer and more difficult).
5. One shares the tools of design and fabricating solutions with the communities and discovers the science underlying the emergent solutions. Share the scientific knowledge so that communities develop distributed technologies for diverse socio-ecological conditions.

First three models were inspired by discussions with Late Dr Kamalesh Kumar, and Dr Y.P. Singh, Hissar Agricultural University, Hisar during the early 1970s. Both of these professors were experts in extension division. Dr Y.P. Singh, in 1967 perhaps guided the first two post graduate thesis on the scientific basis of people's knowledge about livestock care in India in 1967. However, given the difficulties faced among peers (who believed in lab-to-land model and not land-to-lab-to-land model), he did not guide another thesis on the subject till late seventies. This is mentioned here to suggest that scientific peers may encourage as well as stifle the reorganization of scientific culture and value systems. This calls for due caution. To a great extent, the social purpose of science depends on the way we define, differentiate and develop the opportunities for communities, neglected and disadvantaged..

Pursuit of inclusivity in the applications scientific and technological knowledge

There are seven dimensions of inclusivity which affect the extent to which scientific results reach and redefine options for the poor. It is to be reiterated that poor are not a project but are the purpose of science funded by the society. For those unaware, the direct taxes are progressive but indirect taxes are regressive. Through these indirect taxes, the poor thus also pay substantively for the resources that fund scientific and

technological pursuits. They cannot be excluded over any of space, sector, season due to social differentiation or skill.

Inclusive innovations require that problems of high-risk regions (like drought, flood, hailstorm, forest and mountain regions that are difficult to access) are, often bypassed by markets and even by the state, are taken note of, defined and addressed through both short- and long-term solutions. Many of these problems require longitudinal trans-disciplinary research and willingness to bear with the discomfort of travel to these areas for collecting data through participatory processes.

Sectoral exclusion are those domains which have so far not attracted much scientific inquiry. Khadi is one area, handloom is another, small scale artisanal activities, cottage level smelting systems for iron and other materials from the local ore are typical examples. Seasonal fluctuation impedes access and hinders development of time series of data. Then, seasonal migration of the people, particularly pastoralists and labourers also requires dynamic methodologies to maintain cohort integrity in data collection.

Poorer social segments are less articulate. Women headed or managed households dominate these regions and male scientists often find it difficult to interact with women community members in scattered settlement systems. Population density is low and distances are often large among different settlements. Unlike plains, in these regions, people may live far apart. Skills of the local communities in identifying local biodiversity, soil, rocks, weather, wind flow patterns, need to be incorporated in research protocols with their prior informed consent. If ignored, the knowledge base of their traditional skills may even be eroded.

Is it not ironical that such people are often termed unskilled workers, simply because scientists have not established the utility of many of their skills in climate resilience and numerous other developmental activities. At our suggestion, the former President, Dr A.P.J. Abdul Kalam had written to then Prime Minister that work under rural employment program need not be just *menial* but also *mental*. Their skills could have become very important basis of generating knowledge-based enterprises.

Norms of governance also create condition of exclusion when the planning process fails to distinguish the difference in the cost for similar services/studies in low and high population density regions, or difficult terrains. Exclusion of non-human sentient beings and effect of our intervention on their survival and well-being is one of the most neglected aspects of research.

Implication for making scientific pursuits more responsible

A few suggestions are:

a) ***Improving upload to download ratio of content:*** Countries and communities which share more knowledge, acquire leadership position and are able to influence the global narrative more significantly. Not only research publications, findings, data, student assignments, innovations but also half-baked ideas and even futuristic imaginations, need to be shared. Is it not ironical that most startup in health and agriculture train their AI and diagnostic tools on European data because Indians don't share their data, sufficiently as open access. It may be pertinent to mention that the Honey Bee Network has tried to make one of the largest open access innovation database platform at *www.gian.org/databases*.

b) ***Open databases:*** Such databases encourage cross-pollination, democratize the access, reduce the gap between scientists and technologists in privileged positions and the rest, and encourage collaborations across domains. To illustrate: *Hbnkind.gian.org* has around 3000 farmers' knowledge and practices, *Grid.gian.org.in* has grassroots inclusive innovation database (originally developed with UNDP), on rural change and circular economy, innovations for waste management and solving farming problem and a Multilanguage database on medicinal plant for application in human, animal and agricultural ailments https://honeybee.org/plant_db.php.

   Over last three and half decade journey of grassroots innovations and practices published in Honey Bee newsletters are shared here *https://honeybee.org/honeybee_database.php;* and Multilanguage GRI *https://honeybee.org/honeybee_innovation.php*. HBN creativity and inclusive innovation awards (HBNCRIIA) at local and global level are given by GIAN along with HBN institutions. In addition, there are formal sector innovations also shared in open access. One million abandoned US patents in all domains are available at *https://gian.org/abandoned-us-patents/* and over 200,000 projects pursued by 650,000 engineering students are given in *www.https://techpedia.in*.

   Techpedia.in was developed to promote originality among technology students and encourage Kho-Kho model of technological collaboration. The country needs to be an innovation lab. Most of the projects are half baked bricks. They need not always become building blocks or a product in the laboratory of origin but any other student/scientist should be able to take it forward like a relay race and eventually after a few cycles, the translation of an idea into product or service

may fructify. All India Council for Technical Education (AICTE) and University Grants Commission (UGC) may pool such undergraduate and post graduate projects regularly to encourage this model, but it is needed by every country that wants to harness the power of imagination of technically trained youth for shaping an inclusive future. In fact it will be desirable to mandate that engineering student carries out his project in a designated region/village, identifies key problems and unmet solutions and solves them. Besides helping the region, this will also enhance their social connect.

To encourage such activities, Gandhian Young Technological Awards are given to young science and technology students by SRISTI along with HBN institutions *Gyti.techpedia.in* thus making it a platform for early career recognition. Many of the successful deeptech start up, such as COEO lab, Mimyk lab, Shanmukha lab etc., were first recognized by Honey Bee Network and SRISTI through GYTI awards.

c) ***Handling dilemma in translation research:*** When deep science engages with community problems, scientists face challenges. Dr K.S. Krishnan, a famous physicist and former Director of National Physical Laboratory of CSIR narrated one such dilemma to Vishwanath in his book on Organizing for Science (OUP, 1985). In early sixties, he had invited then Prime Minister Nehru to show one of the first solar cookers.. That day was a cloudy day and hence the tea could not be made. Next day, the newspaper headlines were not about what great physics NPL was doing but on the story of unmade tea.

Dr Krishnan recalled that when a scientist does applied work for common people, any person on the street can comment on it. When he works on the deep science, he knows how many people in the world could review it. He found it difficult to deal with such a contradiction. However, this is a genuine dilemma, and scientists have to be enabled to deal with this discomforting reality. Comments by lay people may be unfair and often ill-informed, but on the positive side, they at least show their engagement with deep science. This needs to be welcomed. Such engagement eventually helps common people support deep science endeavors as it happened in space, atomic energy, geophysics for the mining sector.

Communicating science, its contradictions, dilemmas, and paradoxes, has to be discussed openly and transparently, hyperboles and after due diligence, so that society understands the link between basic and applied science in an everyday context, realizes the limits of knowledge at that point of time, and thereby supports the research

in basic science, of which applications may emerge in the longer term.

d) ***The vexed dilemma and frugal solutions:*** A conscientious scientist often faces self-doubt with thoughts such as; Am I attacking the problem at its costlier end? Will poor people be able to afford my solution? Whose choices do I expand? Since I can handle complexity, should my solutions also be complex? Can simple not be optimal?

There are numerous solutions that have been used to address rampant anaemia among women in India. The fact that these problems do not persist only among poor women does not make the task easier. As a part of doctoral research in Cambodia, Charles Walters of Guelph University, Canada, found a robust solution. A 126 g cast iron fish (or any other shape) if put in the non-acidic curry, could leach enough iron for a family of five for five years. The addition of lemon could make this iron bioavailable. It could help overcome a certain kind of anaemia. With iron vessels disappearing from our kitchens, this could be a problem which might have a simpler solution, like cooking every week one dish in an iron vessel.

Similarly, when Balgamia, a government school teacher, found that students, particularly girls were not as attentive and energetic as expected, he got them checked and found that they suffer from iron deficiency. He asked them to bring a handful of pulses and sprouted them in the school. He fed the kids sprouts and in three months, the children regained their original energy and their performance in the school improved. There could not be a more frugal solution. The Gujarat government later introduced sprouts in mid-day meal scheme once a week. Responsible science can lead to affordable, effective democratic, and widely applicable solutions.

e) Sharing results in the local language and in a simple way with those who provide the data makes both—the scientists and the community, wiser. During feedback session, when the community realizes the larger context of the study, they invariably offer new data which was not shared earlier, simply because they did not fathom the larger context of the study, in full measure. Such new data cannot be accessed by any other research methodology. Feedback of scientific investigation is a sound practice on both scientific and ethical grounds. Can this become a standard practice of all community-driven research? Yes, it must.

f) Sufficiency of norms of attribution and acknowledgement of people's knowledge.

Much of the ethno-botanical (I dislike the term ethno for local community knowledge, its a colonial legacy of langauge) and zoological research made people anonymous and rarely these acknowledged the generic communities, neither the specific knowledge generators nor providers, even in a footnote. Correcting this asymmetry was one of the reasons for the emergence of the Honey Bee Network. Today, in HBN database, not only the knowledge providers are acknowledged but wherever applicable, even the scouts through whom the knowledge providers were discovered find a mention. There are many other ways in which knowledge providers can be acknowledged.

With the help of a local team comprising Nadeem and Sabzar, Anamika Dey, pooled the knowledge of a community in Baramulla, union territory of J&K. It was augmented with science and technology by Dr. Mamta Shah, Faculty and the students of L.M. College of Pharmacy, Ahmedabad and supported by GIAN and HBN. The start-up of Anamika mentioned the names of the knowledge providers on the label of Paindel, a pain-relieving oil. One would hardly find such a product worldwide which acknowledges the knowledge providers, inventors on the label of the product. Such business model of innovations make the scientific pursuits truly ethical and responsible.

Earlier, HBN made similar efforts to acknowledge the knowledge provider on the label of the herbal pesticides licensed to a company in Hyderabad. The patent was filed only in the name of the knowledge providers. Following, HBN philosophy, over 1000 patents were filed by the National Innovation Foundation, with the name of inventors and innovators only. Numerous research papers were published with knowledge providers as co-authors. Such a practice might not mean much to the illiterate or semi-literate knowledge providers, but it makes the scientist feel good about themselves. And, their act becomes an example of responsible science and ethical publication practice.

g) Scientific knowledge helps in characterizing, commercializing and conserving biodiversity. Flaxseed was fed to horses and sold 100 kg for about 100 rupees ($1.2). Today it sells 100 gram for a similar amount. So much value addition was created merely by scientific characterization of the grain as a source of Omega-3 fatty acid, so important for vegetarians but also for others. Perilla, found in Nagaland is even richer source of Omega-3 fatty acid besides other vitamins and minerals. As a part of a DBT-supported project, Dr

Anamika and her team found that a pea variety from Gurej valley, union territory of Jammu and Kashmir, had 25 per cent protein but low phytates, anti-nutritive factors making it suitable especially for elderly people. A great deal of biodiversity remains to be properly characterised. Can not all biology departments of the UG and PG colleges teach science by taking wild and domesticated biodiversity for characterisation and feeding back the knowledge to local communities to improve their livelihoods and also conserve the agro- and other biodiversity *in situ*. Similarly, as a part of the same DBT project, GIAN's team found that out of 30 varieties of kidney beans, rajmah, six had more iron content than any other pulse, thanks to the complimentary analysis by Tata Institute of Genetics and Society. So much remains undiscovered on the margin of our country.

h) Leveraging abundant and abandoned resources for inclusive development: scientists can prioritize the analysis of functional properties of abundant and abandoned bioresources so that the poor are not excluded from the respective value chains. Corn silk, often thrown away by farmers as well as consumers of boiled or roasted cob, is rich in antioxidants and is suitable for men with prostate problems and women in UTI problems because of numerous other applications. Thus such a resource being wasted can be a source of survival for the poor who can collect and repackage it as herbal tea. This will be an impactful use of scientific knowledge?

i) Mind of the Margin are not a Marginal mind: this was the subtitle of the book by Anil on Grassroots Innovations (New Delhi: Penguin Random House, 2016). Numerous grassroot innovators have solved rural and urban problems at affordable and accessible level, worldwide. But such success stories have not been documented in textbooks to mould the mind of young and older learners about the potential in blending formal and informal science and technology. Not many of such innovators are invited to the classrooms to share their experiences on how they identified the problems neglected by the mainstream researchers scientists and technologists and then how they resolved the problem at its frugal end. It may be useful if all disciplinary/sectoral associations of scientists and technologists also have exposure to grassroot innovations in the respective domains to learn, share and form bridges for solving problems.

j) It is our firm belief that a change not monitored is a change not desired. There is a need to track the experiments started, paused and modified in response to the feedback from communities or other potential stakeholders of the research. Similarly, there is a need to track action on various suggestions made above.

What next?

Science is basically like an alphabet, Technology is like words, Institutions are like grammar and cultures are like a thesaurus: and these are the four pillars of sustainability. AI tools are changing the speed at which they can process information and data. These tools are also equally capable of curbing curiosity, muting originality and reducing scope for disruptive thinking. Thus, unless AI is fused with RI (real intelligence; i.e. AI+RI), sustained progress cannot be assured. It must be realized that over half the humanity is without the internet, and therefore in AI-based visioning of the future, their vision, ideas, aspiration and knowledge systems remain obscure, untouched and unfelt. Limited documentation of their knowledge in a fragmented and often unethical way cannot substitute the originally expressed and articulated vision of the local communities. The responsible science requires that even AI tools are used with great responsibility lest uninitiated youth fail to recognize their weaknesses and commit major mistakes. It must also be realized that global calamities like climate change, have region-specific implication and these could be resolved only through local contextual knowledge, most being gleaned from traditional knowledge systems. Thus, AI without RI will never be successful.

HBN volunteers pursue *Shodhyatras* every summer and winter which is open to all willing to discover creativity at the grassroots and share prior learning to reinforce the experimental ethics in society. In summer, we walk in hot places and in winter, we walk in cold places. This concept of voluntary suffering helps us to feel and learn from four teachers, teachers within, among peers, in nature and among common people. This is how we touch the ground, we touch the people and update our understanding of social simmering for a more sustainable and inclusive society. In autumn, we have two *Shodhyatra* courses in the Himalayas with IIMA two-year and one-year management students. Having walked more than 7000 Km through every state of the country, many more than once, we believe that such *yatras* may be useful for doctoral and even post graduate/undergraduate scholars to develop *samvedana* (not just empathy) towards unmet social needs.

Sensu-stricto, *Samvedana* is beyond empathy. Empathy is for others, *samvedana* additionally resides within. In Sanskrit, *Sam* means equal and *Vedana* means pain. When we feel the pain of others as intensely as they feel it, it does not remain their pain, it becomes our pain. Then we try to resolve our pain through a driver, *swantah sukhay,* that is, for our own happiness. The journey from *samvedana* to *srijansheelta* (creativity) is not possible without developing a connect to the roots.

It is time we reinforce the connections with roots, look at the integrity of the real ecosystem and leverage the outstanding functional traditional knowledge and contemporary creativity at the grassroots. It is for this reason that Honey Bee Network is now embarking upon creating a distributed and networked Academy of Inclusive Innovation and Traditional Knowledge (AIIKA) or Global Inclusive Innovation Foundation (GIIF). This aims to recognize, respect and reward frugal/MLM innovations for and from the grassroots around the world. Just as deep tech innovations flourished in Silicon valley, the grassroots innovations should be recognized, mentored and upscaled in India. Having spearheaded the grassroots innovation movement around four decades ago, it is only proper that we take the movement to the next stage. AIIKA should not just recognize the innovators but also the scientists and technologists who add value to people's creativity, appreciate the supply chain actors and policy makers who help in scaling up these innovations, and gratefully acknowledge the elders whose traditional knowledge may still have relevance, for functional and futuristic applications for climate resilience, sustainability, inclusive development. More traditional knowledge has been lost in the current generation than ever in the history of humankind due to changes in family patterns and lifestyles. Conserving the relevant knowledge, institutions and cultural diversity along with biodiversity and landscapes are important concerns for sustaining our collective frugal future. The academies have a significant role to play.

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ANIL K. GUPTA, a Padma Shri awardee and Fellow of multiple national academies (FNAAS, FWAAS, FINSA), is a global pioneer in grassroots and inclusive innovation. He serves as Visiting Faculty at the Indian Institute of Management Ahmedabad and AcSIR, and he founded the Honey Bee Network, the National Innovation Foundation, SRISTI, and GIAN to enhance recognition, respect, and rewards for grassroots knowledge systems. His mission is to expand both global and local spaces for innovation from and for communities, bridging informal creativity with formal scientific and industrial ecosystems. Anil K. Gupta has led transformative work in open innovation, frugal engineering and social entrepreneurship, building platforms such as the Honey Bee Network CRIIA Awards and large open-access databases, including engineering student projects

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ANAMIKA DEY is a researcher, educator and ecosystem builder working at the intersection of grassroots innovation, community resilience and inclusive entrepreneurship. She currently serves as CEO of the Gujarat Grassroots Innovation Augmentation Network (GIAN) and is Visiting Faculty at the Indian Institute of Management Ahmedabad and AcSIR. Her work focuses on strengthening pathways for farmer-led innovations, women's knowledge systems, and social enterprises to address climate change and livelihood challenges. She has trained innovation practitioners and policymakers across 115 countries through UNDP's Accelerator Lab Network and has been invited globally by organisations such as FAO, UNESCO, UNESCAP, Oxfam, and the Pontifical Academy of Sciences. Anamika Dey has authored numerous research papers, policy works, and books on open innovation, bio-entrepreneurship, and grassroots incubation. She holds a PhD from IIT-ISM Dhanbad and continues to champion inclusive innovation ecosystems across India and beyond.

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